Photoniques

THE MAGAZINE OF THE FRENCH OPTICAL SOCIETY

Special EOS Issue · March-April 2017

PHOTONICS *in Europe*

INSIGHT
Optics for automotive applications

PORTRAIT
Johannes Kepler

BACK TO BASICS
Computer-generated holograms

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Photoniques
The magazine of the French Optical Society
SFO Société Française d'Optique

21 shades of Photonics

A few years ago, while I was a PhD student and a young EOS member, I happened to receive, once a year, the so-called international issue of the German magazine *Photonik*. It gave me the feeling to be a part of a European project in photonics, with a very special, I would say original and enthusiastic, spirit. For some reason, this recurrent (and much welcome) gift has been stopped – and this has left me orphaned. It has quickly appeared to me, and to the board of the EOS as well, that we had to act towards a renewal of this European action.

Now, why 21 shades of Photonics? Because we are 21 nations gathered in the bosom of the European Optical Society, within near horizons. Think about it: if you take a compass and draw a circle to see what lies within a three-hour flight from Brussels, you will come across all actors of the EOS. These near horizons are galvanizing, and they can help building a common spirit.

This special issue of the French magazine *Photoniques* is intended to work towards that ambitious yet realistic goal: to resume the thread of history with a European issue of a national journal on photonics, and also to help building a common spirit. Please accept it as a gift from a close friend.

Riad HAIDAR
Editor-in-chief

Bonne lecture !

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Special EOS Issue, March-April 2017

Photo credit (cover): © iStockPhoto

Jürgen Jahns
EOS President

Benoît BOULANGER
SFO President

Dear Colleague, Dear Fellow, Dear EOS member,

Optics and photonics are essential areas for advanced science and technology of the 21st century. The science of light is one of the strong fundaments of many areas, ranging from basic physics, chemistry and biology to advanced areas of application. The **European Optical Society** (EOS) is aiming to provide an organizational framework to scientists and engineers who work in academia and industry all across Europe.

Currently, EOS has 21 member societies, 10 of them are EOS Branches, 11 are EOS Affiliated Societies. EOS aims at developing strong ties with all of them and supports various activities of its member societies. Along that line, EOS is happy to announce a new partnership with the French journal *Photoniques*, which already serves as a periodic journal and newsletter for the members of **Société Française d'Optique** (SFO) with five issues per year. Today, we are proud to present the first issue of *Photoniques* in English as a special service to all EOS members.

The rationale behind EOS is indeed to contribute to the advances in optics and related sciences and to bring together the academic and industrial stakeholders of optics and photonics. Benefitting of its already more than 6000 members, and thanks to the support of 21 learned societies representing an equal number of European countries, EOS organizes scientific workshops, conferences, exhibits, runs a scientific journal (http://jeos.springeropen.com/) and much more. Next EOS conferences will be held at the World of Photonics Congress, June 26-29, 2019. These EOS conferences on Optical Technologies come in 4 topics: the 5th Conference on Manufacturing of Optical Systems; the 4th Conference on Optofluidics; the 2nd Conference on Light Engineering; and the 2nd Conference on Optomechanical Engineering. Note that the registration for EOS Optical Technologies conferences includes admission to ALL conferences at the World of Photonics Congress as well as free admission to the LASER World of Photonics trade fair and supporting program! In the beginning of 2017, EOS renewed co-operation agreements with several learned partner societies around the world. EOS members have now the possibility to attend most of the meetings of the EOS partner societies at member rates. These agreements strengthen the mutual collaboration between EOS and the partner societies. The agreements are made to enhance the benefits of members and to serve international optical science and engineering community. Presently, the EOS partners societies are: the Chinese Optical Society (COS); the Japan Society of Applied Physics (JSAP); Optical Society of Japan (OSJ); the Optical Society of Korea (OSK) and the Taiwan Photonics Society (TPS).

On its side, SFO has a long-standing tradition. With approximately 800 individual members and 40 corporate members, SFO gathers French actors in optics and photonics. SFO is a non-profit organization that promotes these two domains as scientific disciplines, and as a vector of technologic innovation in various industries which are largely related to physics phenomena and to the use of light-based technologies. SFO maintains partnerships with academics, industrials, national and international organisms. SFO is a member of the International Commission for Optics (ICO), and it is also the representative of the French community in optics at the European Optical Society (EOS). The driving force of SFO is brought by its 16 thematic clubs that cover a broad spectrum in photonics: Optical Controls and Measurements for Industry (CMOI), Optical Fibers and Networks (CFOR), Optical Thin Layers, Crystals for Optics (JNCO), Fiber optics & Networks, Optics & Applications (HORIZONS), Lasers & Quantum Optics (COLOQ), Laser-Induced Breakdown Spectroscopy (LIBS), Adaptative Optics (JNRIOA-AFOP), Optics & Microwaves (OMW), Guided Optics (JNOG), Photonics and Life Science (PSV), Organic Photonics (JNPO), Physics & Optical Imaging (PIO), Visualization & Image Processing in Fluid Mechanics (FLUVISU). SFO is also very concerned by the teaching of optics with a specific club devoted to the promotion of new pedagogical tools. We have also 5 geographical student clubs joint with EOS. And we are creating a new club devoted to Women in Physics joint with the Société Française de Physique (SFP).

Finally, we hope that you will find interest in the contents of this special issue and in the idea behind it. If you have not done so, visit http://myeos.org/ to discover how you can contribute to this common European base, EOS, and its member societies for the development of optics in its broadest sense.

With our best wishes,

Jürgen JAHNS, EOS President
Benoît BOULANGER, SFO President

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International Commission for Optics (ICO) General Congress

The ICO General Congress has been one of the most historic and authoritative conferences in the field of optics and photonics since the 1st congress was held in the Netherlands in 1948. Following ICO-13 in Sapporo in 1984, in 2017 Japan will once again host ICO-24: which is to be held at the Keio Plaza Hotel, Shinjuku, Tokyo, from August 21st to 25th. With attendees and delegates from all over the world, ICO-24 will include a wide range of topics on optics and photonics, providing a platform for mutual communication between researchers of different fields linked with the main common theme of "Light for Society".

Plenary Speakers:

- **Hiroshi Amano**, *Nagoya University*, *Japan*, "New era of LEDs"
- **Chris Dainty**, *Univ. College London, England*, "Fundamental limits of mobile phone cameras"
- **Anne L'Huillier**, *Lund Univ.*, *Sweden*, "From extreme nonlinear optics to ultrafast atomic physics"
- **Takaaki Kajita**, *Univ. of Tokyo*, *Japan*, "30 years of neutrino researches in Kamioka"

http://ico24.org/

JNOG - JCOM 2017

The joined conferences "Journée du Club Optique et Microondes" and "Journées Nationales d'Optique Guidée" will bring together the francophone scientific community in microwaves-photonics and guided optics, in Limoges (South West of France), from 3 to 6 july 2017.

Registration:
http://www.jnog-omw2017.fr/

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French technology clusters
Route des Lasers and Elopsys merge to become ALPHA-RLH

ALPHA - Route des Lasers & des Hyperfréquences (ALPHA-RLH) is a newly formed technology cluster specializing in photonics, lasers and microwave technologies. It is the result of a merger on 1st January 2017 between two French competitiveness clusters, Route des Lasers and Elopsys.

Based in Bordeaux and Limoges, the cluster is focused on 2 technological fields: Photonics-Laser (laser sources and processes, optical components, instrumentation) and Microwave (integrated electronics, radiocommunication systems, radar systems) and 4 strategic applications:

- Health (medical devices and autonomy): imaging, diagnosis and therapy techniques, technological solutions for people who have lost their independence,
- Communication and security: components or systems for data transmission, data and network security,
- Aerospace and defence: embedded optical/optoelectronic systems, innovative solutions for shaping materials, communication, navigation, and lighting,
- Energy and smart building: solar technology, lighting solutions, energy efficiency, energy storage, connecting or connected devices for buildings.

Digital technology represents a cross-disciplinary activity. It covers digital interfaces, image processing and synthesis, data security and sharing, along with intelligent connecting objects.

Through aggregate skills and expertise, ALPHA-RLH aims to become the French reference cluster in photonics, lasers and microwave technologies. It will enable the cluster to bring out innovation collaborative projects and enrich the support provided to SME members exporting to global markets.

Launching of ALPHA-RLH in Bordeaux – ©MS/CEA.

PYLA, training center for the ALPHA-RLH cluster

PYLA designs and carries out tailor-made training courses, in French and English, on lasers technologies and their applications:

- Metrology, 19-23 June 2017
- Intense Laser Systems, 25-29 September 2017
- Laser Safety Officer, 4-6 October 2017

PYLA is also a partner of the European project IT-ELLI – Innovative Training and Education for Large Laser Infrastructure, led by Bordeaux University. The objective is to develop a global laser safety program with certification at the European level and a laser-based nuclear radiation safety program.
www.pyla-routedeslasers.com

11 cluster members unveiled their innovations at BIOS and Photonics West

As part of a collective export action, ALPHA-RLH accompanied 11 companies at the BIOS and Photonics West trade shows in San Francisco from 27 January to 2 February 2017.
They presented their innovations to the international photonics community, especially novel devices improving imagery, laser accuracy and speed, as well as new ultrafast lasers and optical systems.
Some of these innovations could lead to far-reaching advances in photonics and have an impact on applications for computing, smart manufacturing, IoT, agriculture and medical devices.
A key ALPHA-RLH objective is to support export development and access to new markets.
The US is an important and attractive market for photonics technologies, a significant emerging field with major developments. During the event, the cluster members were able to develop their network and to meet key players.

ALPhANOV won a Prism Award for its GoSpectro at Photonics West

The Technology Center ALPhANOV has been awarded by a Prism Award in the "Detectors and Sensors" category.
GoSpectro is a simple device that turns any smartphone or digital tablet into a light spectrometer. Measure, save and export light spectra... on the go! This enables to perform material characterization and analysis with an ultra-compact device natively connected to the internet, with applications in gemology (gem identification), food industry (color measurement, allergen detection), water quality (pollution detection), academia/teaching, anti-counterfeiting (fluorescent inks), art, etc.

THE UPCOMING INTERNATIONAL EVENTS OF ALPHA-RLH

- **Laser World of Photonics**
  June 26-29, 2017 in Munich (Germany)
  Collective stand with 8 cluster members
- **European Microwave Week** (EuMW)
  October 8-13, 2017 in Nuremberg (Germany)
  Collective stand with cluster members

Back to Photonics West 2017

SPIE Photonics West took place from 28 January to 2 February. Approximately 23,000 scientists, researchers, engineers, students, and others from throughout the global photonics community were among the total attendance at San Francisco's Moscone Center for nearly 100 conferences and two exhibitions, complemented by a course program and numerous networking events.

More than 1,380 exhibiting companies participated in the Photonics West Exhibition Tuesday through Thursday, with even more visitors than last year filling North and South halls to see what is new, including more than 200 new-product launches.

As in the past technical conferences were organized into BiOS, LASE, and OPTO topics, with more than 4700 presentations across more than 95 sessions, with applications tracks in 3D Printing, Brain, and Translational Biophotonics.

LASE @ Photonics West 2017

LASE – the conference dedicated to laser source technologies and industrial lasers and applications was opened and chaired by R. Poprawe (Fraunhofer ILT) and K. Sugioka (RIKEN). In total 654 presentations were announced in 4 sub-conferences with 17 sessions. Impossible to attend all or give a short resume here. It can be noted that fiber lasers, resonators and beam control as well as solid state lasers were the dominating sessions. French companies and researchers are well represented in almost all categories and the exhibition.

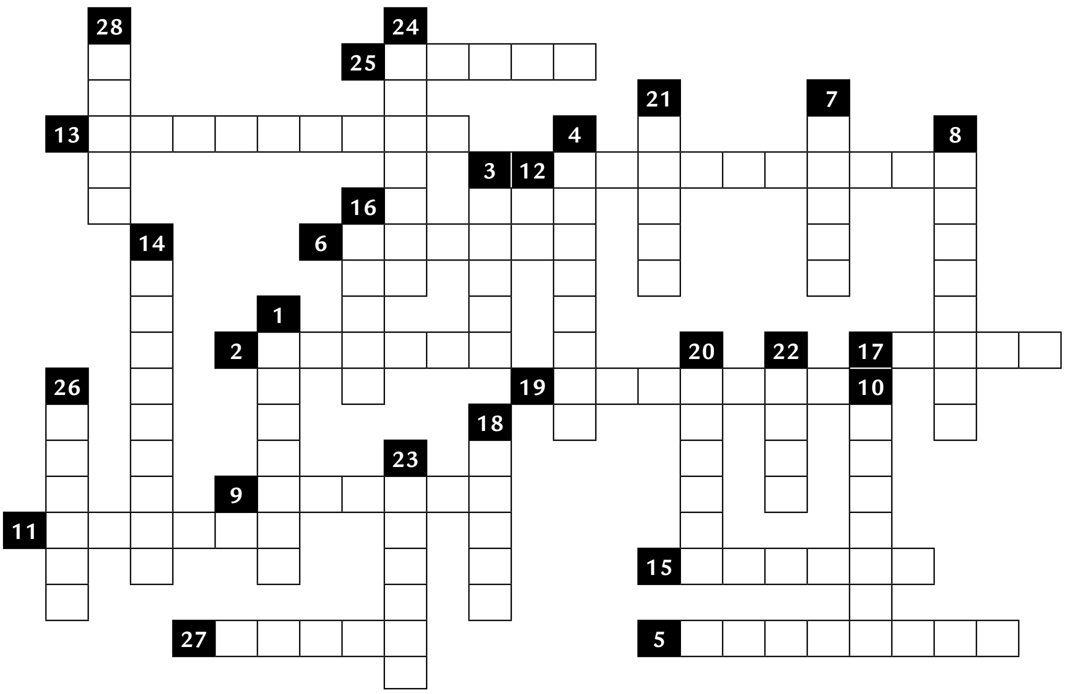
Photonics West continues to be THE networking event for those working in photonics.

OPTO @ PHOTONICS WEST 2017

The OPTO symposium was chaired by Shibing Jian (AdValue Photonics, USA) and Jean-Emmanuel Broquin (IMEP-LAHC, France). The topics include silicon photonics, MEMS-MOEMS, photonics crystals, optoelectronics, semiconductor lasers and LEDS, quantum dots and nanophotonics.

This year the OPTO plenary talks were focused on controlling thermal radiation, quantum dots and LiFi (light wireless communication). Shanhui Fan, from Stanford University, first show how to cool a building during the day. He and his colleagues used a structure made of a stack of dielectric that

CROSSWORDS: FAMOUS OPTICIANS



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1 He illuminates far off
2 He goes the shortest way
3 Does he have an accent?
4 Not an expert swordsman, but a usefull knife-edge
5 No more reflection beyond his preferred angle
6 He rotates mirrors
7 Better in pairs
8 Such a blue sky, my lord!
9 He turned the World into equations
10 The elementary source
11 There is no picture!
12 He combs the light with fish bones
13 He needs two arms for his job
14 Snell's best friend
15 World harmony!
16 He uses mirrors for conjuring trick
17 Rotating sugar cubes
18 The english one for "Cards"
19 Colors forever!
20 He pulls the light to pieces
21 Tasty with fried eggs
22 A unique spot!
23 As sly as a fox!
24 For him, everything is a wave!
25 Father and son, evenly genius
26 He illuminates cities
27 He draws the meridian
28 A line on the right, and a line on the left

reflects the sunlight and emits infrared radiation towards the sky in the 8 to 14 microns range, where the atmosphere is transparent. The universe is used as a heat sink, and he demonstrated cooling at a temperature below 0 °C. Fan also shown that this could be adapted to cool photovoltaic cells, which efficiency drops with the temperature. The stack of dielectric layers does not reflect any more the solar spectrum but transmit it to the photovoltaic cell.

Dieter Bimberg (Technische University, Berlin) plenary talk was focused on the fabrication and practical use of quantum dots in the context of quantum encryption as well as lasers and amplifiers. As he detailed, a quantum dot can emit one or two entangled photons. A LED with a single quantum dot can act as a qubit emitter, and be used in every quantum cryptography processes. A set of quantum dots, with various shapes and sizes can also be used in lasers to broaden the emission of lasers and deliver shorter pulses. Eventually, Dieter Bimberg describe how quantum dots can be used in network amplifiers to decrease their cost and their energy consumption.

The last plenary talk was given by Harald Haas (University of Edinburgh), on the possibilities of using LiFi, *i.e.* wireless communications using visible light. He has made some pioneering work on this promising technology, demonstrating high data rate transmission using LEDs and classical visible detectors. Harald Haas also reviewed some of the common misconception on LiFi, in particular its compatibility with the primary lighting functionality of LEDs and the possibility to transmit data with retro diffused light. He also details his vision of the implications of this technology in the future, and how it can be integrated with public lighting.

P. Bouchon, ONERA | W. Knapp, IRT Jules Verne

Back to EOSAM 2016 in Berlin

The EOS Biennial Meeting (EOSAM), a major European event for the European optics and photonics community, was held in the convention centre of Adlershof in Berlin, September 26–30, 2016. With a full week of interesting optics and photonics presentations in its 8 Topical Meetings, a Grand Challenges of Photonics Session, EU Project Result Dissemination session, workshops, sessions, tutorials and summer school, as well as networking and social events, the EOSAM was attended by over 360 attendees and over 270 presentations and 50 posters were heard and seen during the week.

During EOSAM, EOS announced its new Fellows and awarded esteemed researchers for their contributions to photonics. The new fellows are Roel Baets (Ghent University), Wolfgang Osten (Universität Stuttgart), Carlos Ferreira (University of Valencia), Jürgen Czarske (Technische Universität Dresden), and Anne Debarre, (University Paris Sud and University Paris-Saclay).

Besides, as a legacy of the LIGHT2015 project, EOS continued to award young researchers and entrepreneurs for their outstanding contributions to photonics. This year, it was Camille-Sophie Brès, from École Polytechnique Fédérale de Lausanne, for her outstanding research and work on Fiber and Waveguide Optics.

EOSAM 2018 in Delft. The next EOSAM will be held October 8–12, 2018 in Delft, Netherlands, at the congress centre of TU Delft with multiple topical meetings, tutorials, industrial exhibition and more.

FTTH Conference 2017 in Marseille

What's new in the FTTH domain in Europe?

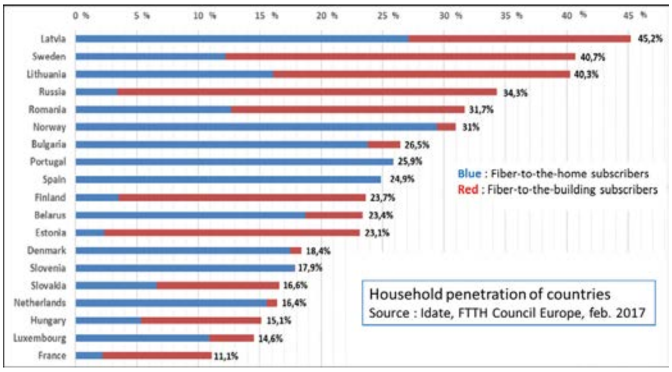
In Marseille (France), the FTTH Council Europe held its annual "FTTH Conference". Three major points: a good affluence in this event, the deployment of subscribers continues and the focus is *"Towards the gigabit society"*.

Building a brighter future

Combining a high-level conference with a leading edge exhibition and unparalleled networking opportunities, this 14th edition of the FTTH Conference remains an international fiber-focused event. During three days – 14-16 February 2017 – about 3000 delegates from 84 countries have participated at 14 conference sessions and 9 workshops held by more than 150 speakers. In the exhibition center, they were around 120 exhibitors and partners who illustrated, with their products and solutions, the theme of the event: *"Building a brighter future"*.

Deployment of subscribers

The number of FTTH subscribers is increasing and positive indicators are present. For the numbers, Idate Consulting gave these figures: at the European level, the number of fiber to the home (FTTH) and fiber to the building (FTTB) subscribers increased by 23% over the first nine months of 2016 and the number of "homes passed"[1] increased by 17%. So, they were more than 44.3 million FTTH/B subscribers and nearly 148 million FTTH/B homes passed in EU39 at September 2016. In EU39, Idate Consulting noted that 17 countries have more than 2 million homes passed and 9 countries have 1 million subscribers or more: Russia, Spain, France, Romania, Sweden... On household penetration of European countries, only 12 have a mature market with a rate higher than 20% (cf. illustration). The best penetrations are for Latvia, Sweden, Lithuania, Russia, Romania, Norway... France is 19th with a rate of 11.1%.



Positive indicators were presented by Graham Finnie, an independent consultant, who insisted on the fact that line speeds continue to rise steadily, pushing network operators towards FTTH; 4k TV, smart TVs, video streaming and device proliferation. Other factors mentioned were: any incumbents have shifted strategy towards FTTH; Eastern Europe generally is leaving DSL behind; competing and collaborative building are important catalysts in many countries; technology innovation (*e.g.* micro trenching) is also helping to reduce costs; *etc.*

Towards the gigabit society

The focus topics at the heart of this 14th edition of the FTTH Conference were inspired by the new Gigabit connectivity targets and the legislative proposal for a new European telecoms rulebook by the European Commission. It was completed by the approach of new services and technologies enabled by very high capacity networks to enhance our lives. But, the main question was: at what cost? A cost model calculated the complete overlay of the EU28 countries with FTTH including 100% homes passed and 50% connected. The outstanding costs are €156 billion for the already existing fiber coverage and connections. The re-use of existing infrastructure and effective implementation can lead to further 12% cost savings and could further bring down these costs to €137 billion. More precise explanatio ns are expected for the 15th edition of the FTTH Conference that will be held in Valencia (Spain) on 13-15 February 2018. We hope to meet you at the venue: Convention & Exhibition Center Feria Valencia!

Jean-Michel MUR, Jm.mur@orange.fr

[1] The number of "homes passed" is the potential number of premises to which an operator has capability to connect in a service area (but the premises may or may not be connected to the network).

Inpho Venture Summit: Europe is brimming with innovation

Technological innovation and entrepreneurship is on the rise in Europe, say panelists at INPHO Venture Summit, a financial investor and strategic business partnering event focused on growth market investments.

"*This year's conference provided a productive forum on the convergence of hardware technologies, such as photonics, and software capabilities, such as big data analytics, to open up new opportunities for startups,*" said George Ugras, chairman of the 2016 edition and managing partner at IBM Ventures.

Thales sponsored this year's conference, hosting attendees from a range of industries and the international financial community. The event engaged investors and leading industrial players in discussions on high investment opportunities in growth markets.

For many who attended InPho, it was a *"thrill to see photonics impacting fields other than telecom, such as connected cars and digital healthcare,"* said Steve Alexander, CTO of Ciena.

The Telecom Panel pointed to the regulatory environment as a challenge in competing for new revenue streams. Nevertheless, Julian Lucek, Juniper Networks, said that as capacity grows, within five years products will need to offer eight times the performance. Amongst areas offering opportunities for growth he listed the need for new ASIC, memory bandwidth for packaging forwarding, new physics and silicon photonics.

Predicting disease was highlighted as an area where digital technologies could play a major role, in particular in devices that "understand" how our bodies *"react to the daily treatment,"* said Mark Lightowler, CEO of Phorix Ltd. Inaki Gutiérrez-Ibarluze, knowledge manager at HTA, raised digital issues concerning privacy, data accuracy and security and interoperability.

The IoT and Smart Grid Panel talked of the rising trends in converging energy and digital technologies. The two market drivers are: decentralization, where the scale of economies will be reached with distributed energy such as solar PV or windmills; digitization, where flexibility and dispatchable energy sources linked to renewable energy growth will be required to provide a digitally controlled and stable supply.

The autonomous car offers unlimited opportunities for sensors and other smart system technologies. However, due to the requirement for the right infrastructure to be in place the horizon for truly self-driving cars is likely to be another 20–30 years away.

Europe is a good environment for developing innovation according to the panel led by Nitan Pathak, partner at the European Investment Fund (EIF).

Europe is now focused on *"bridging the gap between the end of the research phase, when the financial system of subsidies and grants are no longer available, and the period enabling startups to scale-up,"* said Willy van Puymbroek, head of the Unit, Competitive Electronics Industry at the EC.

Private money can *"bring the breakthrough in enabling European startups to migrate to the next stage,"* said Jean-Louis Malinge, investment manager at Arch Venture Partners. *"But there is the need for more European blockbusters to motivate the financial community,"* added Christian Reitberger, partner at Wellington Partners.

The next edition is planned for October 11–12, 2018 (Bordeaux) with the support of the cluster ALPHA-RLH, the CEA, BLUMORPHO and the CCIBG.

Carol Leslie,
Andrew Lloyd & Associates

Johannes Kepler

The German mathematician and astronomer Johannes Kepler is above all famous for discovering the eponymous laws governing planetary motion. Combining Tycho Brahe's meticulous observations and his own theoretical predictions, his astronomical tables were some of the most enduringly accurate ever established. They provided a firm footing for Copernican theory in the face of the then universally acknowledged model of a geocentric universe. Despite poor eyesight that prevented him from carrying out original experimental research, he became a major figure in the field of optics, overhauling all its fundamental concepts and developing a sound mathematical approach that supported Galileo's first telescopic observations.

Riad HAIDAR, haidar@onera.fr


A portrait of Johannes Kepler

MAIN DATES

Born 27 December 1571, Weil der Stadt (Germany)	
1601	*Mathematicus imperialis,* Prague
1609	First two Kepler laws
1611	*Dioptricae* publication
1619	The Harmony of the World's third law
Deceased 15 November 1630, Regensburg (Germany)	

Johannes Kepler was born on 27 December 1571 to a family of modest means in the town of Weil der Stadt. His father Heinrich Kepler was a mercenary in the Duke of Württemberg's army. His mother Catherine was the daughter of an innkeeper, and sometimes brewed herbal remedies that earned her the reputation of a healer. Born prematurely, Johannes had a sickly constitution. At the age of 3 years, he contracted smallpox, which almost killed him and left him with very weak eyesight and deformed hands. The Lutheran Protestant Keplers lived a peaceful existence in the Holy Roman Empire, then under the reign of religiously tolerant Maximilian II. In 1576, they moved to Leonberg near Stuttgart, where they opened an inn.

When Johannes was 9 years old, he and his father excitedly witnessed the total lunar eclipse of 31 January 1580, watching the Moon gradually disappear as it passed through the Earth's shadow. This experience made a deep impression on the young boy, and he was to return to it many years later. He was then a pupil of the local Latin school, but in 1583, he entered the Protestant seminary in Adelberg, later graduating to the upper seminary of Maulbronn.

In 1589, his father took up arms once more, never to return. That same year, Johannes became a student at the famous Stift seminary of Tübingen University, founded in 1536. He now seemed firmly set on the path to ordination, although he was not entirely at ease with the Lutheran current of thought set out in the Augsburg Confession of 1530, which then held sway at Tübingen.

At the Stift, he studied philosophy, philology, Greek and above all mathematics, under the supervision of astronomer Michael Maestlin [1550-1631]. As Kepler was both a brilliant and an open-minded student, Maestlin decided to introduce him to the heliocentric theory put forward by Nicolaus Copernicus [1473-1543]. In a world dominated by the Church and the geocentric model devised by Claudius Ptolemy [ca. AD 90 – *ca.* 168], which placed the Earth at the centre of the universe, this act was nothing short of unlawful. However, his teacher's arguments were so compelling and the reasoning so seductive that Kepler soon became a convinced Copernican. As this new stance was obviously incompatible with the role of a pastor, Kepler abandoned his theology studies and took up a post of mathematics teacher at the Protestant school in Graz in 1594. He also became the official astrologer of Archduke Ferdinand of Habsburg.

Early mathematical research

Kepler married Barbara Müller on 27 April 1597. It was a love match, arranged by his family. A peasant woman with a forceful personality, Barbara bore him three children and took care of all the household affairs. However, she then contracted Hungarian spotted fever, the couple lost their 6-year-old son Friedrich to smallpox, and she herself died one year later, in 1612.

Kepler rapidly clarified his scientific views, setting down his initial thoughts about planetary motion and how the universe is ordered in *Mysterium Cosmographicum*. Published in 1596, this work placed him firmly in the avant-garde of astronomy. Brilliant and passionate, and at times movingly naïve, it was the first convincing plea for Copernican theory. It also lay the foundations for a whole new science – astrophysics, for unlike his contemporaries, Kepler was also interested in the causes behind the organization of the planets.

In his book, Kepler proposed a model of the solar system based on regular polyhedra. He pictured a *soul* that attracted inert bodies towards the Sun and induced planetary motion. He even attempted to formulate a mathematical law to describe it, linking the planets' orbital period to their distance from the Sun. This was a splendid intuition, but one based on misconceptions about optics and dynamics, and obviously required more mature reflection. Indeed, it was to take him two decades of thought and effort to fathom out the harmony of the world.

https://doi.org/10.1051/photon/2017S212

Mathematicus imperialis

His theory of solids put Kepler, then an obscure maths teacher in Graz, in contact with some of his most illustrious contemporaries, including Tycho Brahe [1546-1601], the Danish astronomer responsible for the building of the Uraniborg (literally: Castle of Urania), probably the most important observatory in Europe at that time, and later Galileo Galilei [1564-1642]. Since 1599, Tycho Brahe had held the post of mathematicus imperialis at the court of Rudolf II in Prague. Extremely impressed by the *Mysterium Cosmographicum*, he invited Kepler to join him. It was an extraordinary opportunity that arose at exactly the right time, for because of his Protestant faith and Copernican ideas, Kepler was facing exile. He duly took refuge in Prague in 1600, and become assistant mathematician to Tycho Brahe.

For some years, Brahe had been struggling with the inextricable mystery of the Martian orbit. As a result of his work at the Uraniborg, he had precise, reliable and comprehensive astronomical observations to work on, but was unable to make anything of them. Fortunately, while Kepler's eyesight was too poor for him to observe the night skies, he was extraordinarily good with figures. He immediately entered into the spirit of the enterprise, and continued to wrestle with the problem even after Brahe's death in 1601, when he succeeded him as imperial mathematician. This exceptional post, which he occupied until 1612, afforded him privileges he could never have dreamed of as the son of an innkeeper and mercenary.

Understanding the Martian orbit was a massive challenge. According to classical astronomy, which Kepler still espoused (though not for much longer), planets followed a circular orbit, so it should only take a few observations to establish all the parameters. The welter of data amassed by Brahe meant he could easily calculate several sets of parameters and refine them to his heart's content. Working out the orbit should thus have been child's play – a couple of months of routine calculations at the most. The problem was that Mars continued to resist him not just for a few months but for six whole years. The orbit of Mars was not circular – that much was obvious. Like all his contemporaries, Kepler found himself trapped by ancient models and mired in the astronomical certainties of the day, and it took all his powers of inventiveness and intellectual daring to extricate himself. He allowed his imagination free reign, and after much doubt and hesitancy, eventually accepted what his intuition was telling him – that the Red Planet follows an elliptical path around the Sun. Better still, he realized that the line connecting Mars to the Sun sweeps out equal areas in equal times. These areas can therefore be used as a measure of time. By studying the orbits of the other planets in the solar system, he was able to prove the universality of what are now known as the First and Second Laws of Kepler, which he published in *Astronomia Nova* in 1609. It is impossible to overstate the importance of this discovery. For a start, Isaac Newton [1643-1727] drew on Kepler's law to deductively calculate his Law of Universal Gravitation. Kepler had now entered the pantheon of geniuses of humanity.

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Optics

As he tussled with Mars, Kepler become aware of the importance of understanding optical concepts and phenomena if he was to pursue his astronomical research. This was not a culture with which his mentor Maestlin was familiar, and he therefore had to acquire this knowledge on his own, studying the works of the English medieval thinker Roger Bacon [1214-1294] and the Arab scientist Alhazen [965-1039]. In 1604, he published *Astronomiae Pars Optica*, in which he described the first ever mathematical study of camera obscura and refraction, expressed as the law $I = n \times r$ (small-angle approximation of Snell's law). He was also interested in the mechanism of eyesight, and supported the hypothesis that images are projected onto the retina. His first book about optics was essentially a state of the art, but presented from an astonishingly modern angle with the practical objective of serving Kepler's astronomical research. His second book, *Dioptrice*, published in 1611, was rather more original. In it, he established his theory of lenses and their combinations, and explained the working of the telescope that Galileo had just used to discovered the satellites of Jupiter.

Kepler enjoyed 10 peaceful and scientifically very productive years in Prague, occupying a comfortable and prestigious position. In 1611, however, the fates dealt him several cruel blows, with the deaths of first his son then his wife, and the abdication of his protector Rudolf II in favour of the latter's brother Matthias. Worse still, his scientific views were viewed with such deep suspicion by the Church that he was excommunicated in 1612. Thus, for a multitude of reasons, the atmosphere in Prague suddenly became oppressive and Kepler was forced to leave the imperial capital, settling in the Austrian town of Linz.

Now a widower, the former imperial mathematician became a very eligible bachelor, and was soon being assiduously courted. His choice fell upon Susanna Reuttinger, the daughter of the hotelier in the neighbouring town of Eferding, who was to bear him seven children. Theirs was a happy marriage, and an amusing anecdote illustrating Kepler's insatiable curiosity is that while he was purchasing the wine for his wedding breakfast, he noticed that the volume of the barrels was estimated by inserting a rod diagonally – an archaic and inaccurate system. He therefore turned his attention to the solids of revolution, calculating their capacity using the method of indivisibles (a precursor of infinitesimal calculus). He published his results in *Nova Stereometria Doliorum Vinariorum* in 1615.

In the same year, his mother Catherine was accused of witchcraft – a serious charge that could have led to her being burned at the stake. Johannes Kepler intervened, and a lengthy six-year court case ensued. At one point his mother, then aged 70, spent several months behind bars in Güglingen, but she was eventually found not guilty and acquitted in 1621.

The Harmony of the World

Despite his exile in Linz, Kepler remained first and foremost an astronomer. His work was sustained by the deeply held conviction that the Universe is governed by harmonic laws. This faith in the harmony of the world (*Harmonices Mundi* was the title of a book published in 1619 in which he assigned a musical theme to each planet) led him to make the troubling, improbable and fantastic discovery of his third law, according to which the square of the orbital period of a planet is directly proportional to the cube of the semimajor axis of its orbit. So intense was this moment of supreme intuition that he recalled the thrill of its discovery in his description of the law.

Calculating astronomical tables was an integral part of an astronomer's or imperial mathematician's work. Kepler had never shirked this chore, despite its tedium. The logarithms invented by John Napier [1550-1617] in 1614 nevertheless came as a great relief both to him and to all his contemporaries, although they remained rather mysterious and their reliability was therefore questioned in some quarters. Kepler was personally convinced of their soundness, and in response to the rampant scepticism of his former mentor Maestlin, he set out to explain how they worked and demonstrate their mathematical relevance in his *Chilias Logarithmorum*. In the process, he improved on Napier's mode of calculation, using a geometric method to establish a new logarithmic table.

In 1627, Kepler published his magnum opus in Ulm, known as the *Rudolphine Tables*, a masterful compendium of all his work as a mathematician and astronomer, together with the observations made by Tycho Brahe. Remarkably, given the rapidly developing knowledge of heavenly bodies, these tables remained accurate for several decades – a dazzling confirmation of the accuracy of Kepler's Laws and the relevance of the Copernican model.

Ultima verba

Kepler died after a short illness on 15 November 1630, at the age of 59. He was buried in the Bavarian town of Regensburg, but in 1632, during the Thirty Years War, the Swedish army destroyed his grave. His manuscripts were discovered in 1773 and retrieved by Catherine II of Russia, and are now kept at the Pulkovo Observatory in Saint Petersburg.

It is hard for us today to imagine the intellectual journeys undertaken by the bold, resolute and politically astute scholars who forged the science we practice today and built the world as we know it. Kepler is one of these scholars, as he revolutionized our vision of the Universe and set us off on a path of discovery that we are still following today, as we revolve relentlessly around the Sun, amidst the stars at the heart of our galaxy. ■

FURTHER READING

[1] J.-P. Luminet, *L'oeil de Galilée* (J.-C. Lattès, 2009).

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AUTO 2.0 : *photonics inside*

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Photonics manufacturers are always on the lookout for new application fields beyond the more established markets in defence, science and telecommunications, in order to sustain the growth of their sector. About 15 years ago, the introduction of powerful lasers for welding, marking or cutting glass and metal gave photonics a toehold in the motor industry, but its use since then has mainly been confined to the outside of the vehicle, with the notable exception of headlight optics.

This is despite major reductions in costs over the past two decades, not just in production, but also in aftercare and maintenance. We have moved from the early technology that was prohibitively expensive and required the expertise of astronomers or military personnel to the mass production of tens of millions of cheap and extremely reliable car parts. These tumbling costs and the emergence of new needs have created exciting opportunities for in-vehicle photonics. As we will see below, photonic devices will mainly be used to acquire a highly accurate picture of the vehicle's environment and communicate this information to the driver in as natural a way as possible. Radar and sonar technologies already allow us to analyse the immediate environment, but mapping wider areas requires new technologies.

So what are the latest products and how widely are they being used?

A rapidly growing world market for cars

While the statistics for France's automotive industry generally make for gloomy reading, the global market continues to enjoy sustained growth. Production plunged to around 64 million light vehicles per annum in the wake of the economic and financial crisis of 2008, but by 2013 it had bounced back to more than 83 million vehicles, and most industry observers expect it to top the 100 million mark around 2019.

This growth is mainly being driven by rising purchasing power in emerging nations. Above a GDP (at purchasing power parity) of $10,000 per capita, car ownership goes up significantly, stabilizing at around 500-600 per 1000 people (rate achieved in most OECD countries). Countries like China, Malaysia and Turkey are currently hovering around this threshold, reflected in a massive increase in new consumers.

These new consumers have a very different perception of cars from the one that prevails in Europe, and

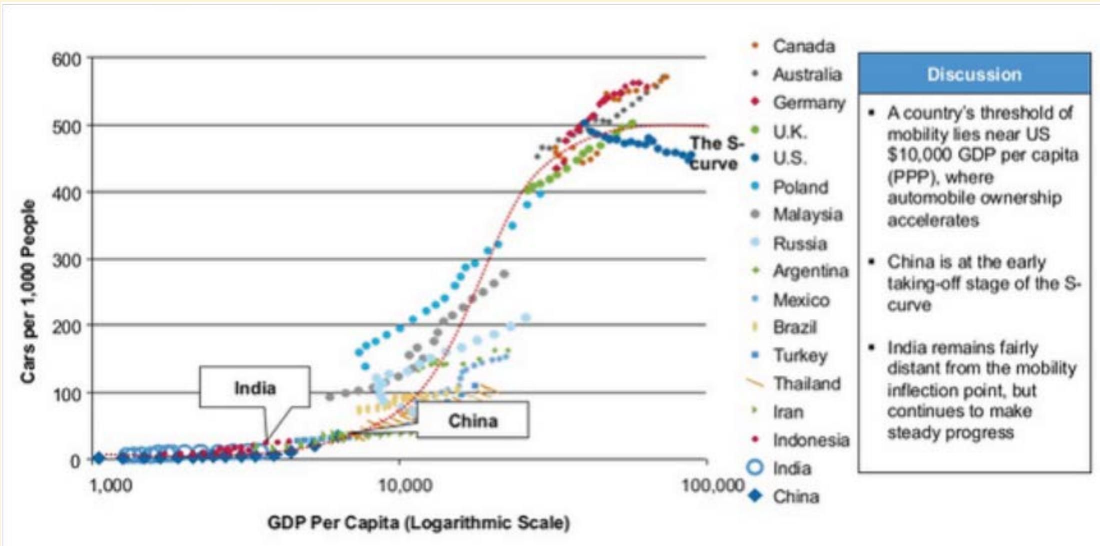

Figure 1. Number of registered motor vehicles per country (source: *China Automotive Industry Yearbook*, 2014).

automatically assume that they will be connected (e.g. vehicle-to-vehicle, vehicle-to-infrastructure, vehicle-to-home). This, of course, is good news for two areas of the photonics industry in particular (information display and 3D mapping).

Vehicles assembled closer to their markets

Although this growth in consumption is having an impact on motor production and assembly, with a major shift to East and Southeast Asian countries (from 8% of production in 2000 to 36% in 2014; see *Fig. 2*), it has not so far dented European production, which has remained stable at around 20 million vehicles per annum for the past 15 years.

Within the European Union, Germany is currently home to 20% of all assembly plants (41 out of 208) and 30% of Europe's production of motor vehicles. In 2014, France produced 1.8 million vehicles at 33 plants. These figures give us a good idea of the size of the different markets that are accessible to photonics:

- parts and systems for light vehicles: 80-100 million vehicles;
- parts and systems for luxury cars: 10% of world production (i.e. 8-10 million vehicles), mainly manufactured by Mercedes, Audi and BMW;
- systems for production lines: approximately 1000 assembly plants (20% in the 28 countries of the European Union);
- testing systems (headlamp beam testers, crash tests): 100 or so testing and R&D facilities.

Strong growth in photonic products and technologies

The market for in-vehicle photonic components (i.e. first five categories listed in *Table 1*) was estimated to be worth **$16.7 billion in 2013, and is expected to rise to $26.7 billion by 2018**, corresponding to a mean annual growth of 9.8% over the next 5 years. This growth is unevenly distributed across the different segments, being mainly focused on advanced driver assistance systems (ADASs) - technologies that will ultimately give rise to automated vehicle (AV) solutions. The ADAS market is expected to grow by 21.4% - growth that should be set against the far more modest growth of the automotive market (3.2%) and megasuppliers (3.0%) over the same period (source: Roland Berger management consultants, 2013).

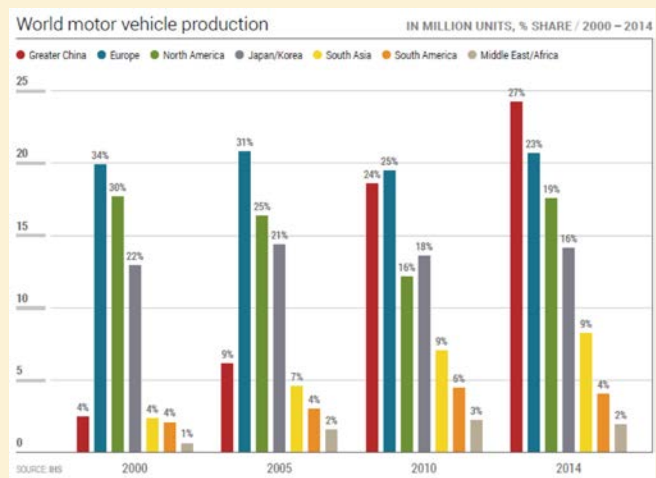

Figure 2. Motor vehicle production in each geographical zone (source: Information Handling Services (IHS), 2014).

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Where?	In the Car						Car Manufacturing	
Types of Systems	Sensing and imaging systems	Communication systems	Screens, Displays, Projectors	Systems based on LED, OLED and other sources	Photovoltaic systems	Laser systems	Sensing and imaging systems
Photonic Functions	Acquiring information	Transmitting information	Delivering information	Light providing	Energy providing	Processing	Acquiring information
Products examples	- Imaging: CMOS cameras, IR cameras ... - Sensing: Various types of sensors (see figure below) - Proximity and gesture control	Optical communication systems in cars: - MOST networks, - FlexRay ...	Displays for: - Entertain-ment, - Driver information, - GPS information, - Others ...	Lighting systems (inside & outside the car) based on: - LED, - OLED, - Lasers ...	Photovoltaic devices for energy providing in cars.	Laser systems for: - Welding, - Cutting, - Drilling, - Marking ...	Non Destructive Testing & QA/ QC: - Machine vision, - Reflectometry, - Thermography - Profilometry - Shearography ...

Table 1. Photonics components according to function (source: Tematys, 2015).

Lighting: a market undergoing a major overhaul

Optics made early inroads into the automotive industry via lighting, where the light from halogen, xenon and now light-emitting diode (LED) headlamps needed to be distributed as efficiently as possible. This continues to be the most important segment (more than 62% of value in 2018), and is undergoing increasingly rapid technological advances, as shown in *Figure 3*.

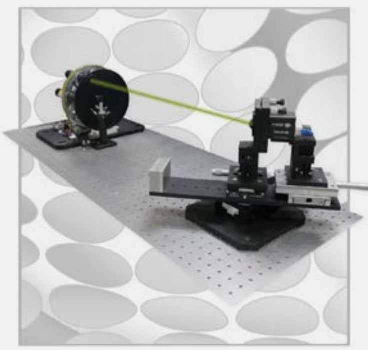
The simultaneous advent of new, energy-efficient light-source technologies (LEDs and possibly lasers), display technologies, digital image processing, and greater in-vehicle integration is giving rise to very high value-added advanced frontlighting systems (AFS) that reduce glare to oncoming vehicles and may, in the medium term, be used to signal to pedestrians.

In-vehicle equipment dominated by Asia

Following in the wake of network telecommunications developments, the early 2000s saw growth in both in-vehicle communication systems (transceivers and plastic optical fibre (POF) transmission) and low-cost components (photodiodes, LEDs for automotive interior lighting) for noncritical systems. Production of these components mainly took place in Asia (Taiwan, Japan, South Korea, then China).

Fisheye lenses for ADAS

In the motor industry, the term *fisheye* refers to the ultra-wide-angle lenses used in ADAS. If they are to deliver reliable identification in variable and complex environmental conditions, they must have uniform contrast across the field of view and for the whole of the visible spectrum. Their high level of intrinsic distortion must also be calibrated, in order to guide the identification algorithms.
It is vital to optically characterize these lenses so that the best ones can be selected and the suppliers' compliance with specifications can be checked. To gauge the actual impact of a lens on image quality, it is not enough to measure the optical transfer function (OTF). Wavefront measurement does, however, meet the needs of manufacturers, as it gives direct access to all the components of the light transmitted through the lens. In partnership with Renault, Phasics has developed a rigorous, automated polychromatic test bench that supplies the OTF, aberration and distortion values for the optical system's exit pupil in a single acquisition for each field of view.



△ Test bench developed by Phasics

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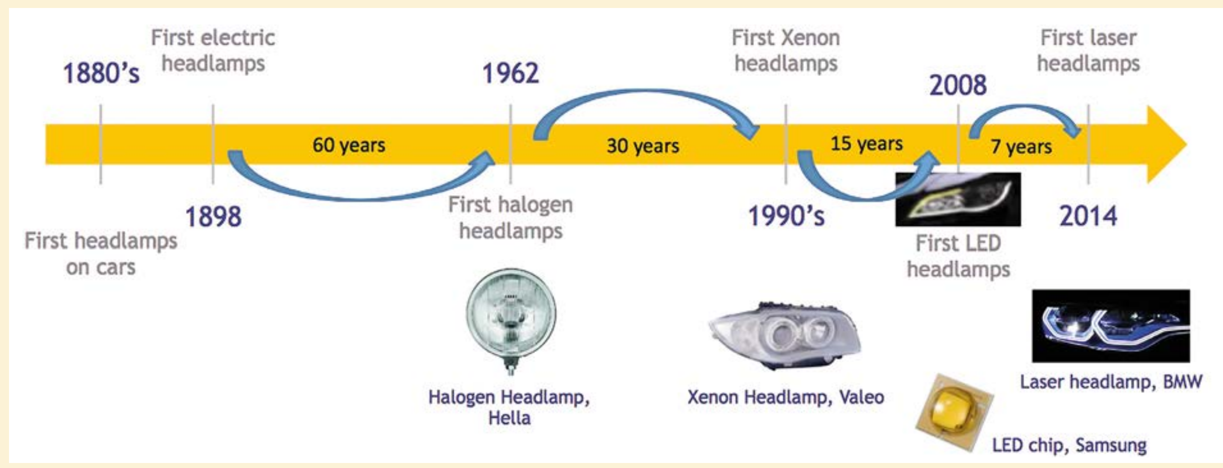

Figure 3. Changes in motor vehicle lighting (source: Tematys, 2015).

Assisted driving: considerable potential for growth

Today, however, the greatest potential for growth lies in driver assistance, which is set to undergo massive expansion within the near future. In 2014–2015, six of the largest parts manufacturers (Bosch, Magna, Continental, Denso, Hyundai, ZF) embarked on major development and integration programmes. Bosch, the world leader, reported a doubling of sales of cameras and radars between 2013 and 2014, and they almost doubled again over the previous 12 months. As for motor manufacturers, Toyota had equipped the whole of its range with ADAS by the end of 2016, while Renault intends to do the same for many of its models over the next 3 years. As Cap Gemini's 2015 report made clear, many consumer countries are already looking beyond driver assistance to self-driving or driverless cars.

The cameras and radars that are currently on the market clearly have limitations when it comes to, say, authorizing a vehicle to automatically change lanes. By providing 360° digital images of the environment, light-detection and ranging (LiDAR) sensors will prove crucial for automated driving in environments that are simple to model, such as motorways and bypasses. Valeo and its partner Ibeo, along with Bosch, which already has more than 10 sensors developed in house (cameras, radars, LiDARs), are expanding the footholds established by Velodyne for in-vehicle LIDARs and Vitronic for infrastructure LiDARs. Experts predict that, in 4 years' time, the market for these cameras, novel sensors and innovative display modes will be worth in excess of €8 billion.

These components still have one or two technical issues affecting their reliability in complex environments (e.g. rain or fog), while costs remain prohibitive (Velodyne's second-generation LiDARs have a hefty price tag of $30,000), but in a few months' time

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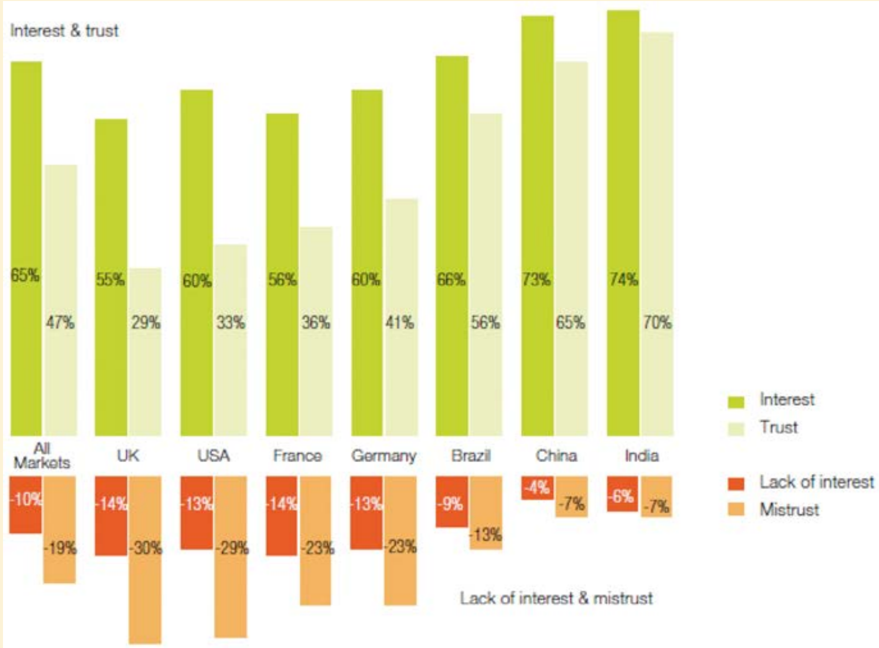

Figure 4. Interest and trust in self-driving cars by country, 2015 (source: Cap Gemini).

we should start to see prices plummet to below €1000 with no significant loss in performances.

Alongside these components, most future growth is expected to be in data analysis software. With the increasing use of sensors, the data they yield will have to be organized and analysed in real time, be it for safety purposes or for monitoring driver vigilance. This will offer opportunities for new players to come into the motor industry. The Israeli company MobilEye is already working with most of the world's leading parts manufacturers to deliver safety diagnoses, while French firms such as Innov+ and Chronocam are positioning themselves in specific market segments (e.g. driver vigilance assistance).

Potential pitfalls facing the photonics industry

Photonics offers the only means of generating a 3D map of the environment (via visible-light and infrared cameras, and LiDARs), meaning that today's radar-based and ultrasound sensors will be relegated to secondary roles in the future. The first markets (premium and luxury ranges) for this new technology represent 10-15 million vehicles. If the 70 million vehicles in the lower categories are to be equipped, costs will have to be substantially reduced (which is precisely what the manufacturers of visible CMOS cameras are doing).

Recent changes in the way that polluting emissions are measured, and the

	INTERIOR				
	IMAGING	SENSING	LIGHTING	COMMUNICATION	DISPLAYS
COMFORT	Cameras for rear passengers observation	Spectroscopy for air quality monitoring IR active systems for gesture recognition	Halogen lamps, Neon lamps, LEDs, Optical fibers OLEDs		LED/LCD for dashboard
ENTER-TAINMENT			Diffractive optics*	MOST (Media Oriented Systems Transport) for communication between media in the car Plastic Optical Fiber	LCD, electrochromic displays, ... for passengers

Table 2. Photonics components for the vehicle interior (source: Tematys, 2015).

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	ADAS				
	IMAGING & SENSING INSIDE	IMAGING & SENSING OUTSIDE	LIGHTING	COMMUNICATION	DISPLAYS
SAFETY	Thermopiles for detection of passengers presence Cameras for driver drowsiness monitoring	Photodiodes, IR sources for rain detection, luminosity monitoring, ... Backup camera LIDAR and cameras for collision avoidance, traffic sign recognition Active and passive IR systems for night vision and pedestrian protection	Adaptive frontlighting systems	Optical communication (VLC, ...) for V2V and V2I communication	Head-up displays (HUD) (holography, projectors, augmented reality)

Table 3. Photonics components for ADAS functions.

environmental impact of these emissions in new consumer countries (China, Malaysia), will require the development of devices to measure emissions of pollutant gases and particulates not just on the outside of the vehicle but also, probably, on the inside, too, as the air quality of vehicle interiors is particularly poor. This will open up new markets for a whole range of spectroscopy components.

These fast-growing markets are not just attracting the attention of photonics manufacturers. The problem of vehicle emissions measurement has led to the development of very reasonably priced electrochemical solutions. In the fields of vehicle-to-vehicle and vehicle-to-infrastructure communication, WiFi offers an attractive alternative to LiFi, with established standards and a wide range of available expertise, plus the ability to spread development costs across huge fields of application and, ultimately, support the cost reductions inherent to the motor parts market. As for in-vehicle communication, the winner so far in the competition between Ethernet and media-oriented systems transport (MOST) fibre-optic transceivers has been the standardized Ethernet technology, as the MOST format has failed to make headway in other application markets.

Although these new photonic technologies will benefit from the large automotive markets in the medium term, they still need to find other major applications if leading manufacturers are to come together and set industry-wide standards. It should also be borne in mind that there is no point collecting good-quality information if it cannot be properly analysed and exploited. It is therefore vital for photonics and IT manufacturers to team up to ensure the lasting development of in-vehicle photonics. ■

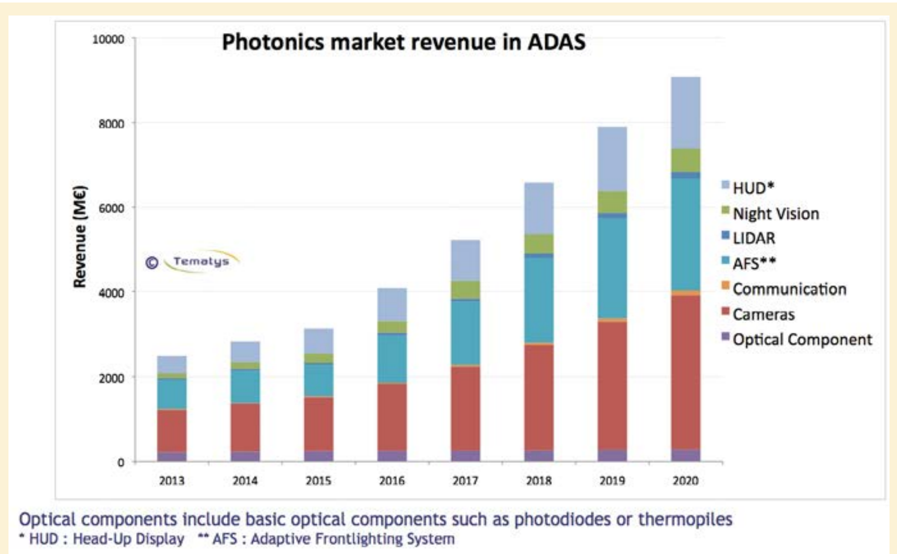

Figure 5. Photonic component market for ADAS functions (source: Tematys, 2015).

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ULTRABRIGHT single-photon sources

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The development of a quantum communication network will require sources that efficiently emit single photons. Now, using a new lithography technique that garnered a silver CNRS medal in 2014, it has recently proved possible to fabricate these sources using quantum dots (QDs), that is, artificial solid-state atoms. Performed at cryogenic temperatures, this technique makes it possible to position a single QD in the middle of an optical microcavity with nanometric precision.

Inefficient quantum light sources

One major hurdle in the development of quantum optical technologies is the manufacture of efficient single-photon sources. This type of source should ideally emit a single photon on demand, in a well-defined mode of the electromagnetic field[1]. At present, optical quantum communications and computation protocols use heralded single-photon sources, where a pair of photons is generated by nonlinear parametric frequency conversion, and the detection of one photon signals the arrival of the other. To avoid generating too many light pulses containing more than one photon, these sources operate at flows where less than 5% of pulses contain a pair of photons, the others being essentially empty. This situation is far from ideal, as it dramatically reduces the rate of optical communication and, in the broader field of quantum computation, restricts the complexity of the calculations that can be performed.

Semiconductor quantum dots offer new promise...

The past 15 years have seen the emergence of another approach to fabricating these sources. It involves the use of nano-emitters, known as semiconductor QDs. One semiconductor material of nanometric size is inserted in another, forming a highly effective

[1] An attenuated laser is not a source of single photons. Although the photons are emitted in a defined field mode, the photon statistics are Poissonian. This means that even when the pulses contain less than one photon on average, the probability of a pulse containing two is non-negligible.

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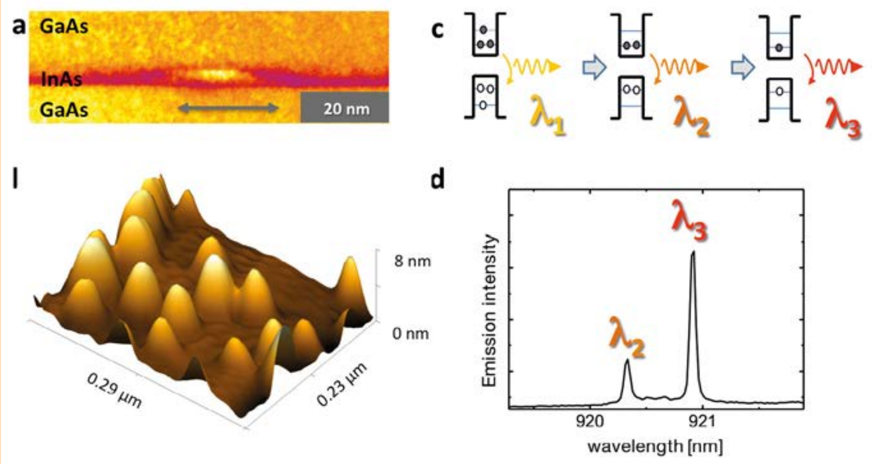

Figure 1. Semiconductor quantum dots. **(a)** Transmission electron microscope image of a single quantum dot (with the kind permission of G. Patriarche and A. Lemaître, C2N-CNRS). **(b)** Atomic-force microscope image of a plane of quantum dots (with the kind permission of C. Gomez-Carbonell, C2N-CNRS). **(c)** Functional diagram of single-photon emission: when several electron-hole pairs are created in the quantum dot, the system emits several photons one after the other at different wavelengths. **(d)** Typical emission spectrum of a quantum dot at 10 K.

electron trap [1]. The carriers in this type of nanostructure have discrete energy levels, like the electronic states in a single atom. When a large number of carriers are created in a QD, the system goes back to its ground state by emitting successively several photons. Their emission wavelength depends directly on the number of carriers in the QD, so that at a given wavelength, on one photon is emitted. These objects are ideal single-photon sources, in that for each excitation pulse, there is an almost 100% probability that the QD will emit a single photon [2].

The problem is that they suffer from the same drawback as all semiconductor light sources, namely the difficulty of collecting the emitted light, which is mostly trapped inside the material by total internal reflection. Although the QD does indeed emit a photon at each excitation, less than 1% actually emerge from the device. This problem can be overcome by controlling the way the QD is coupled to light. As E. Purcell predicted in 1946, spontaneous emission is not an intrinsic property of the emitter, but depends on its electromagnetic environment [3]. Placing a point emitter in an optical cavity can increase its coupling to a particular mode of the optical field and accelerate its spontaneous emission in this mode. For this to happen, two conditions must be met: the QD must be placed at the confined optical field maximum, and must be in spectral resonance with it.

... but how can we control them?

Meeting these conditions has proved challenging. QDs self-assemble from differences in lattice parameters when indium arsenide is grown in a gallium arsenide matrix. These QDs are therefore totally randomly located. To make matters worse, they measure just 20−30 nm wide and are only a few nm thick, corresponding to ten or so atomic layers. The slightest variation in their shape or composition therefore significantly changes their emission wavelength. In this context, traditional fabrication methods, which cannot control the QDs' spatial and spectral positions, have yields below 0.1%.

A great deal of time and effort has been devoted to solving this problem. Some researchers have tried to force QDs to grow on predefined networks. However, these promising methods have yet to result in QDs with satisfactory optical qualities. Other techniques that have been tried involve using atomic force microscopy to detect individual QDs. Each one is mapped with respect to gold markers, and electron-beam lithography is used to fabricate a cavity aligned with these markers [4]. Further technological stages are then required to fine-tune the nanocavity mode into resonance with the quantum dot exciton. These techniques are quite spectacular, although they are difficult to accomplish and have not been reproduced.

Is *in situ* photolithography the solution?

The Center for Nanoscience and Nanotechnology (C2N) of the French National Research Centre (CNRS) has come up with an original approach whereby the location of a QD is optically measured, and a cavity centred on this QD is defined using laser lithography [5].

To achieve this, a photoresist is deposited on a sample containing self-assembled QDs. This sample is placed in a cryostat to lower its temperature to 10 K, so that the QDs emit extremely pure single photons. A red laser beam excites QD emission without exposing the photoresist (*Fig. 2a-(I)*). The diameter of the laser's excitation spot is limited by diffraction (approx. one micron), but the excitation of the nanometric-sized QD depends on local excitation density. This means that by moving the emitter within the excitation beam to maximize its emission, it is possible to measure the QD's position (*Fig.* 2a-*(II)*). Just as the summit of a mountain several kilometres wide can be located to within one metre, a QD can be localized to within 50 nm. The next stage in this *in situ* lithography technique involves using a green laser, accurately superimposed on the red laser, to expose a pattern in the photoresist centred on the QD, in order to directly define the optical cavity (*Fig. 2a-(III)*). Finally, the cavity's geometry is adjusted so that it is precisely tuned with the QD's known emission wavelength. These localization and writing stages can be repeated, enabling a large number of

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devices to be manufactured in a single lithography stage. The cavities are then etched using techniques normally employed to etch optoelectronic devices.

First demonstrated with micropillar cavities, produced by etching a cylinder measuring a few microns in diameter from a planar Bragg cavity sample, *in situ* lithography has since been used to accurately place QDs in various types of cavities. To enhance the technique's potential, the CNRS has teamed up with the private company attocube to develop an *in situ* lithography technology that has been used since 2010 to make more complex structures, including so-called connected pillar cavities allowing electrical control of the device [6], coupled cavities [7], and hybrid plasmonic-dielectric cavities.

Ultrabright single-photon sources

Inserting a QD in a cavity makes it possible to modify its spontaneous emission and fabricate extremely bright single-photon sources. This may look like an oxymoron, but as the QD emits a photon at each optical excitation, *brightness* refers here to the probability of collecting that photon. In the absence of a cavity, this brightness is hardly few percent.

When it is coupled with a cavity, the QD's emission rate in the cavity mode is accelerated by a factor F_P, whereas in other optical modes this emission rate remains unchanged. The probability of the QD emitting its single photon in the cavity mode is thus $p = F_P/(F_P+1)$. With a moderate ($F_P = 3$–5) acceleration of spontaneous emission, the probability is nearly 75–85%. With a judicious choice of cavity geometry, it is now possible to produce in a controlled and reproducible fashion sources that emit single photons on demand with 80% brightness [8]. These sources are 20 times brighter than any of those used today in the field of optical quantum information. Moreover, as it takes a QD approximately one hundred picoseconds to emit

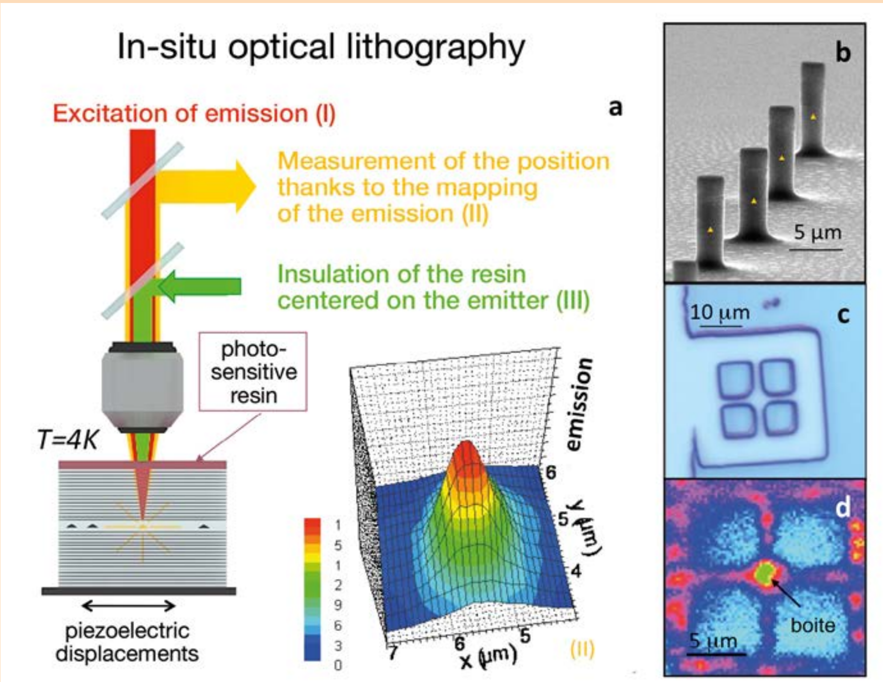

Figure 2. (a) Functional diagram: a red laser allows the position of quantum dots to be measured by mapping their emission (bottom right). A green laser is used to expose a pattern centred on the selected quantum dot in the photoresist. (b) Scanning electron microscope image of micropillars fabricated using this technique, each with a single quantum dot in its centre. (c) Optical microscope image of a connected pillar structure [6] etched in the resist. (d) Emission mapping of the device shown in (c) indicates a strong emission signal from the quantum dot at the centre of the pattern.

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a single photon, these sources can be used at frequencies up to the GHz range. Most recently, they have been shown to generate highly indistinguishable photons, a key requirement for many quantum applications [9].

A whole new potential to explore

These single-photon sources could potentially bring about a critical increase in the complexity of quantum computation, as well as in the speed of quantum communications. Andrew White's group in Brisbane, Australia, a founding group in optical quantum technologies, embarked on this adventure 3 years ago. Working closely with this group, the C2N team has already set up a quantum logic gate with an ultrabright QD source [10]. More recently, they have demonstrated first Boson sampling measurements using the C2N QD sources, demonstrating a 200 speed-up in the manipulation of three photons as compared to the same measurement conducted with usual sources [11].

In situ lithography does not serve solely to fabricate efficient single-photon sources. With clever cavity geometry, it has proved possible to make the brightest source of polarization-entangled photon pairs so far [7]. Just as we can efficiently collect the single photons emitted by a QD, so we can ensure that every photon sent to the device interacts with the QD. This property has allowed us to demonstrate optical nonlinearities on the scale of just a few photons, thus opening the way up to the implementation of logic gates on the single-photon scale [12]. Moreover, inserting a charge carrier in the QD creates a device that can rotate the polarization of a photon by several degrees, depending on whether this carrier is in a up- or a down-spin state [13]. From this point on, many things are possible. Fabricated with optoelectronic tools, these devices could, for example, allow the development of solid-state quantum networks where the photons generated by QDs act as flying qubits, linking spin quantum memories! ■

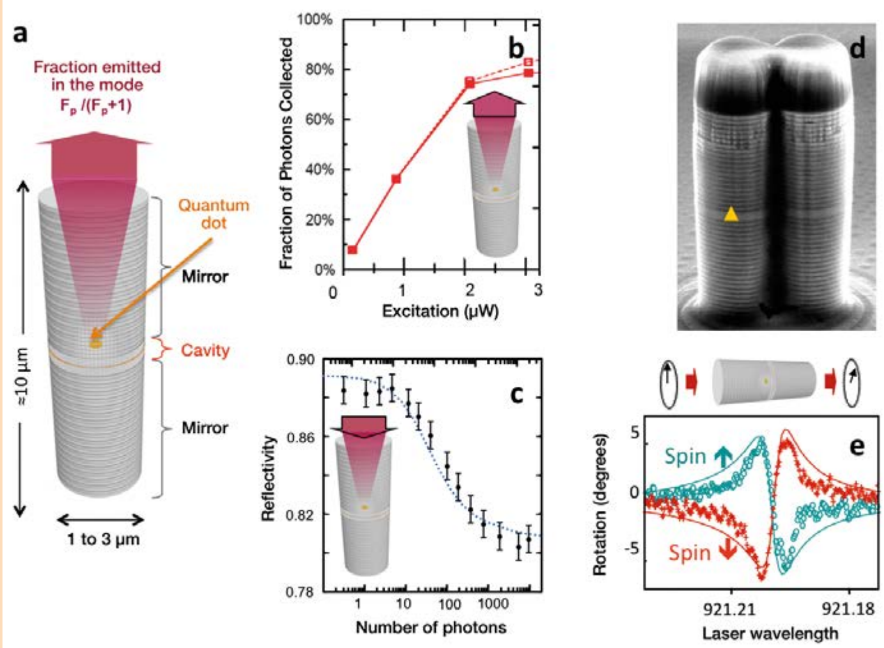

Figure 3. (a) Functional diagram of a micropillar cavity and light extraction through acceleration of spontaneous emission. **(b)** Probability of collecting the single photon emitted by the quantum dot according to excitation power. At saturation, brightness is 80% [8]. **(c)** Demonstration of an optical nonlinearity obtained for just 8 photons by measuring quantum-dot cavity system reflectivity [12]. **(d)** Electron microscope image of an ultrabright source of polarization-entangled electron pairs [7]. **(e)** Photon polarization rotation of ±6° induced by a single spin in the cavity, depending on whether the spin is up or down [13].

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SURFACE PLASMON RESONANCE IMAGING: application in microbiology

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Surface plasmons can be defined as the collective oscillation of free electrons on a metallic surface. They were first observed back in the early 20th century, by the American physicist and inventor R.W. Wood, while he was studying the diffraction of light by a metallic grating. Wood observed very narrow absorption bands in the diffraction spectrum that would remain unexplained until 1941, when U. Fano demonstrated that they were associated with surface waves known today as *surface plasmons*. A similar phenomenon explains the colours of stained-glass windows in cathedrals, as the glass contains metallic nanoparticles with plasmon absorption bands in the visible spectrum.

Surface plasmon resonance (SPR) is induced by incident photons. This resonant coupling can only take place if several conditions are met [1]. First, the real part of the metal's permittivity at the excitation wavelength must be negative. This is the case for gold, silver and aluminium in the visible and near-infrared spectrum. Second, the wave vector of the incident light must match that of the surface plasmon:

$$\frac{2\pi}{\lambda} n_{inc} \sin\theta = \frac{2\pi}{\lambda} Re\left\{\sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m+\varepsilon_d}}\right\}$$

where θ is the angle of incidence, λ the incident wavelength, n_{inc} the refractive index of the incident medium (prism in *Fig. 1*), and ε_m and ε_d the permittivities of the metal and the dielectric (water in *Fig. 1*). Surface plasmons are actually just one (classic) example of waves guided by total reflection, but at the interface between a dielectric and a metal sheet.

The coupling condition is usually achieved with an optical configuration developed by E. Kretschmann and H. Raether in 1968 [2], in which transverse magnetic (TM)-polarized incident light passes through a prism coated with a metal film (*Fig. 1*). The coupling between the photons and the metal's electrons manifests itself in a sharp drop in reflectivity for a particular angle of incidence, determined by the incident wavelength.

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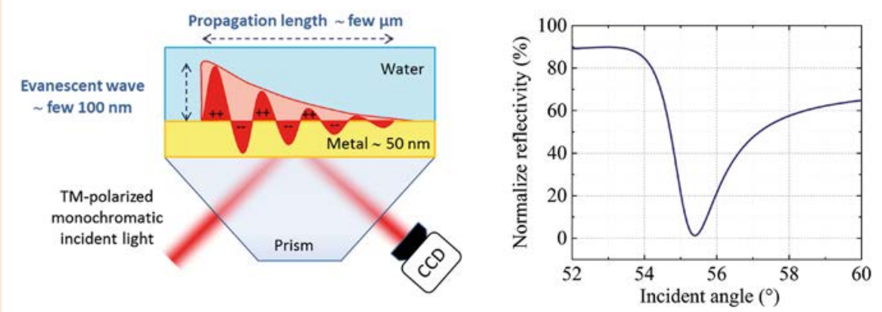

Figure 1. Diagram illustrating the principle of an SPR system: a quasi-monochromatic, collimated TM-polarized light illuminates a metallic film deposited on a prism. An evanescent, plasmon-type wave is generated at the metal-water interface, resulting in an absorption resonance within an ultra-narrow angle (less than 1°).

The excited surface plasmon propagates along the metal-dielectric interface. This evanescent wave typically has a penetration depth of several hundred nanometres and a propagation length of several microns. It was the sharpness of the resonance and the evanescence of the surface plasmons that led to the use of SPR in sensors, which first appeared on the market in the early 1980s.

Principle of SPR imaging

Most commercial and research SPR systems work in exactly the same way. A collimated, quasi-monochromatic beam, generally in the red spectrum for greater sensitivity, is directed through a prism onto a 50 nm-thick gold film deposited either on a glass slide or else on the prism itself. The detection principle relies directly on the resonance (dependent on the permittivity or refractive index of the dielectric above the gold film) and evanescent quality of the surface plasmons. In this coupling condition, the optical device becomes a transducer that converts local variations in the optical index in the vicinity of the metal to large optical signals, as a result of changes in the coupling efficiency between incident light and plasmons. Insofar as these variations in the index are proportional to mass density, SPR sensors can be regarded as optical microbalances, accurate to within a few picogrammes per mm^2.

Numerous detection configurations have been devised to measure these resonance shifts. The one with the simplest instrumentation – and also the most widely used – consists in measuring variations in incident beam reflectivity, preferably at the steepest slope in the plasmon resonance. A camera is used to track these variations in reflectivity across the entire gold surface, resulting in plasmonic imaging (SPRi). A microfluidic system is generally placed on the metal surface, so that the substances to be analysed can be sequentially injected. For example, the adsorption of a single layer of organic molecules

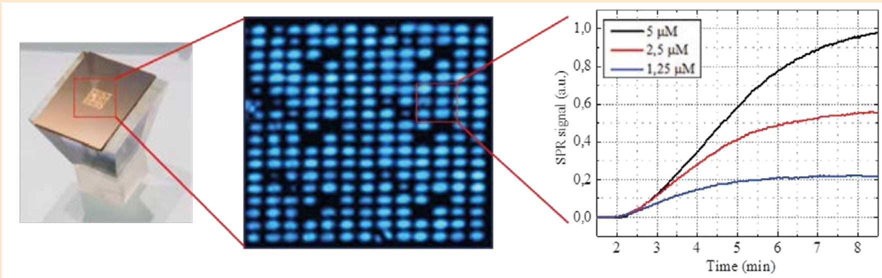

Figure 2. Photo of a functionalized gold film, showing the microarray of probes on the chip. Image of reflectivity variation in SPRi (pseudo-coloured) after a DNA-DNA interaction. Example of kinetics measured on three families of probes with different surface concentrations.

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of nanometric thickness typically brings about a variation in incident beam reflectivity of nearly 2%. The same molecular adsorption on a plain glass slide with no gold film would yield a variation of just 0.00002%. The metal film and the surface plasmons therefore amplify sensitivity fivefold.

As with other biosensors, biochips derive their specificity from their surface functionalization. The main strength of SPRi sensors is that they do not need any secondary marker on the target molecule (so-called *label-free* technique). Rather, it is the variation in the optical index close to the gold layer, brought about by the arrival of the molecules, that is detected. This avoids all the constraints linked to marking, such as the marker's impact on the interaction under scrutiny, photobleaching for fluorescent markers, and end-point readings. All SPRi systems therefore rely on some form of surface chemistry to enable target-specific molecular probes to be attached to the gold surface. A wide range of surface chemistries have been developed, allowing virtually every major class of biomolecule to be attached, including oligonucleotides, antibodies, proteins and peptides. Between several tens and several hundreds of probes can be deposited on the surface of a single chip, meaning that the interactions between a single target molecule and a large number of probes can be studied simultaneously [3]. The other advantage of SPRi is that the measurements are made in real time, allowing for video-rate imaging of reflectivity across the chip (*Fig. 2*). This enables probe-target kinetics to be captured, and association and dissociation constants to be determined.

Application in microbiology

When a very small number of bacteria need to be detected – typically between one and several hundred, the standard methods used in the fields of medicine or food processing for microbiological diagnosis rely on the growth properties of these bacteria. There has to be an incubation period of at least 18 hours before any analyses can be performed, and it generally takes at least 36 hours for a pathogenic agent to be identified [4]. Such lengthy waits are extremely problematic if pathogenic organisms urgently need to be identified. For example, as fresh foodstuffs are highly perishable, they are sometimes put on sale before the results of bacterial tests are known. This obviously represents a health risk for customers, as well as an economic risk for manufacturers, should a contaminated product subsequently have to be withdrawn from supermarket shelves. Similarly, in the medical field, rapid identification of an infectious pathogenic agent allows patients to start on the most appropriate – and therefore most effective – treatment at an earlier stage. There is thus a very real need to introduce new, more efficient tools that can look for and rapidly identify several pathogens at the same time.

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Figure 3. PlasmoChip and MonoPresto marketed by Prestodiag.

SPR systems offer a simple means of identifying bacteria in real time, without any markers. The bacteria interact with specific ligands grafted on the chip, bringing about a local change in the refractive index in the vicinity of the surface and thus a plasmonic resonance signal [5]. Using SPR systems in imaging mode allows numerous different probes to be attached to the chip's surface, meaning that numerous pathogens can be simultaneously identified in the course of a single test. When proteins and/or antibodies are used as biorecognition molecules, it is possible to detect up to several hundred specific pathogens in the space of just a few hours. This SPR detection method is currently used in bacteriology to detect microbiological pathogens in foodstuffs.

The PlasmoChip biochip (*Fig. 3*), which can be microarrayed with ligand spots (up to 70 per well) allows for the multiplex detection of pathogenic agents. Depending on the specificity of the ligand that is used, which can range from a peptide to a monoclonal antibody, it is possible to detect bacteria with more or less precision, from a whole genus down to a specific serotype, with a detection threshold of approximately 10^5 bacteria per mL.

Figure 4 illustrates the detection of one particular pathogenic bacterial strain: *Cronobacter* sakazakii. In just 10 minutes, there is specific recognition of the antibodies and a significant variation in the signal from the C5a and C5b antibody spots specific to this particular bacterial strain, demonstrating the presence of this bacterium growing in the solution.

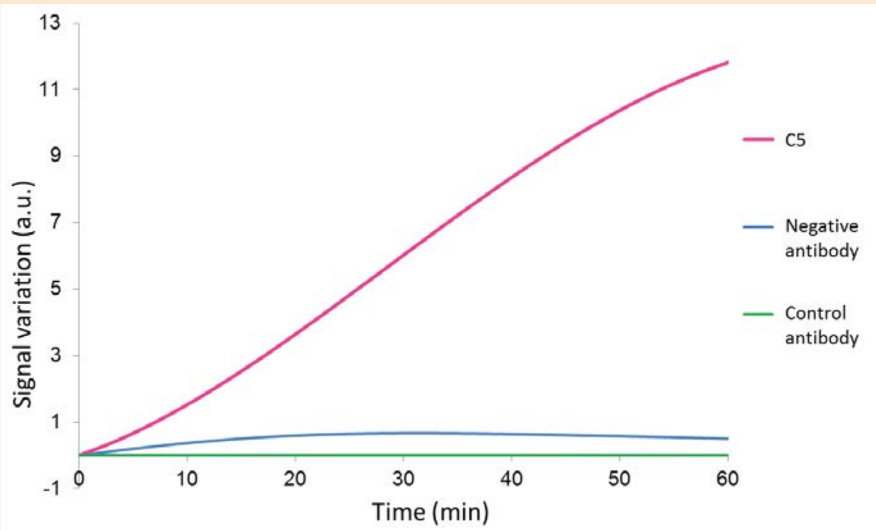

Figure 4. Kinetics of the various ligands measured during the detection of the pathogenic bacterium *Cronobacter* sakazakii.

The main advantage of using SPR systems to detect bacteria is that analyses can be performed in complex environments. Because they operate in reflection configuration (i.e. opposite side to the medium being analysed), readings are largely impervious to the turbidity, or rather the opacity or absorbance, of the environment. Lastly, as the plasmon field is only sensitive to a depth of a few hundred nanometres, it is relatively unaffected by the potential presence of bulkier compounds (food fragments). This is a considerable advantage over other spectroscopic or colorimetric techniques which, by their very nature, can only work in *clean* environments. It is this compatibility with complex environments that makes SPR systems so suitable for use in the food processing field, where tests often need to be carried out rapidly on opaque beverages (e.g., milk) or cloudy mixtures where foodstuffs have been put in suspension.

When a foodstuff is contaminated by a pathogen, the latter's concentration is far below the detection threshold of the analytical systems that are currently on the market and, as we saw earlier, a bacterial culture therefore has to be performed, in order to increase the concentrations of the different populations. Using SPR systems in the *culture/capture/measure* mode can take several hours, but is still

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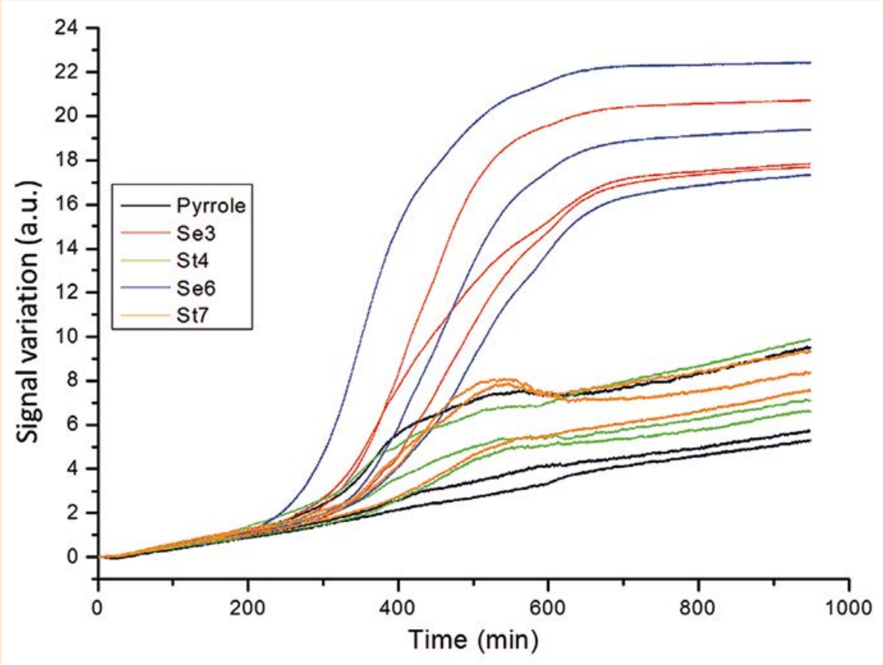

Figure 5. Detection of ~ 10 *Salmonella* Enteritidis bacteria in raw cow's milk.

faster than standard techniques [6]. *Figure 5* illustrates the analysis of raw cow's milk contaminated with ten or so *Salmonella* Enteritidis bacteria. This particular raw milk possessed a highly developed natural bacterial flora, in the order of 10^6 bacteria per mL. The aim was therefore to detect solely the pathogenic strain(s), from among the many nontarget bacteria. Only Se3 and Se6 antibodies specific to the *S.* Enteritidis strain exhibited an exponential increase in the SPR signal, reflecting bacterial growth. Some individual pathogenic bacteria can therefore be specifically detected in fewer than 10 hours.

To conclude, SPR and SPRi are proving particularly suitable for carrying out microbiological analyses of complex samples, as these techniques require no marking, take place in real time, and can be multiplexed. Biochip use makes for considerable flexibility and high specificity of the ligand arrays for the target bacteria. Nonetheless, a better understanding of the mechanisms by which bacteria bind to antibodies, and how they multiply close to a surface, through more accurate observations at the single-cell level, could allow for even more targeted, and thus more rapid, assays for pathogenic bacteria. ■

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TERAHERTZ wireless communications

III/V photonics: a basic THz communications technology compatible with fibre-optic networks

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The growing capacity of wireless networks, driven mainly by new uses and growing mobility, has created a need for new communication systems. The terahertz (THz) frequency range, corresponding to long optical wavelengths (very far infrared) and very high-frequency electronics (at the limit of a transistor's intrinsic capacity), is a prime candidate for these applications.

The need to communicate has always spurred the development of technology for transmitting information. Copper wiring, for instance, with its limited transmission capacity, has been outstripped by technologies that send light beams down thin optical fibres over long distances (undersea or metropolitan networks), while on a smaller scale, optical links are replacing data buses in high-speed calculators. These technologies are increasingly reliant on so-called *silicon photonics*, as its high level of integration brings far greater compactness.

Internet Protocol (IP) traffic is constantly increasing, with monthly traffic expected to reach 130 exabytes (1 EB = 10^{18} bytes) by 2018 [1], and the next revolution for the first half of the 21st century will therefore be the advent of technologies allowing for the massive development of wireless communication. However, although changes in use mean that the greatest growth is expected to be in wireless communication networks, these are still the weakest link in terms of data rate, even though more and more online services are now mainstream.

Since G. Marconi's experiments in the early days of radio, carrier frequencies (carrier waves convey information) have become ever higher, and wireless transmission systems will be exploiting the terahertz range of frequencies (1 THz = 10^{12} hertz) by 2020 [2], if only to increase communication network capacity between each base station. The Shannon-Hartley theorem, which allows us to calculate channel capacity ($C = B \log_2 (1 + S/N)$, where C is the capacity in bits/s, B the bandwidth in Hz, and S/N the signal-to-noise ratio), reminds us that any increase in capacity must be matched by an increase in bandwidth B. The problem is that the electromagnetic spectrum is becoming increasingly crowded. This led to the recent opening of new frequency bands, first at 60 GHz, then in the E band in the 71-76 GHz and 81-86 GHz ranges (1 GHz = 10^9 hertz). However, these new frequency bands only offer data transfer rates of around 7 Gbps per subband (although this could increase to around 10 Gbps with advanced signal coding), and operating frequencies will have to increase beyond 100 GHz if we are to achieve rates in the order of several dozen Gbps. Circuits generally have a relative bandwidth of just 10 or 15% with respect to the central frequency. As a result, the THz frequency range (0.3-30 THz for optical physicists, and 0.1-10 THz for electronics engineers), has been the focus of attention for several years now, as researchers attempt to resolve the problem of ultra-fast wireless communication. Moreover, with the development

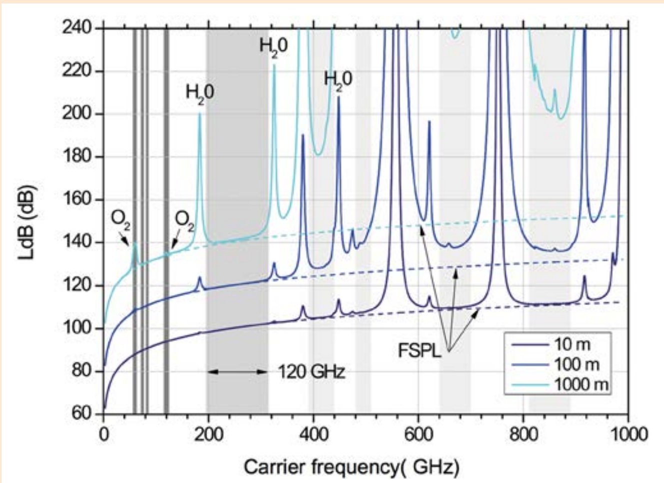

Figure 1. Link budget for the THz range (atmospheric attenuation (dB/km) obtained from spectra.iao.ru/en/en/home/ for 2.59% H_2O).

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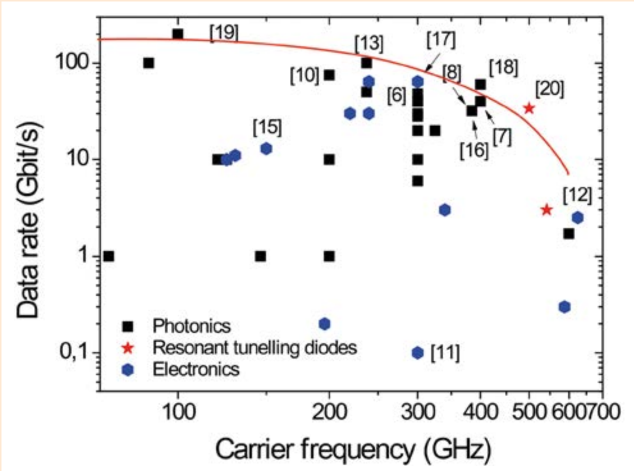

Figure 2. State of the art (data rate/ carrier frequency) in THz communication.

of fibre-to-the-home (FTTH) passive optical networks (PONs), the convergence of radio and fibre technologies is even more relevant today, in the form of fibre to the antenna (FTTA).

Once the technological building bricks have been identified, we will still need to identify the ad hoc frequencies for free-space propagation. Atmospheric absorption is restricted to isotropic path loss (link budget for omnidirectional antennae) up to a distance of 1 km (*Fig. 1*) for frequencies at the upper limit of the millimetric band, above 220 GHz. The major advantage here is that bands above 275 GHz have not yet been allocated to specific applications. Standardization attempts are currently underway at the Institute of Electrical and Electronics Engineers (IEEE), where an interest group is looking into the introduction of a standard for 100 Gbps at these frequencies [3].

We can therefore confidently predict that, by 2020, the THz spectrum will have been explored with a view to using it for ultrafast wireless communications. We can reasonably assume that the data rate for commercial wireless communications will reach 100 Gbps within the next decade. This level will be vital for the real-time transmission of high-definition video flows. For example, the output signal of an HD camera has a rate of 1.5 Gbps, so compression techniques are required to adapt it to the limited bandwidth of conventional transmission channels (approx. 20 Mbps).

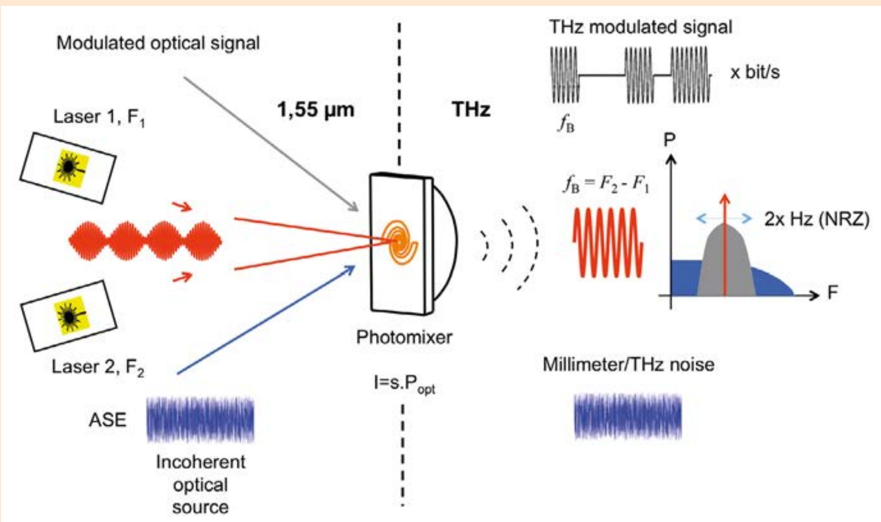

Figure 3. Photomixing technique for generating a THz signal in continuous mode (red), as either a non-return-to-zero (NRZ) amplitude-modulated signal (grey), or an incoherent signal (blue).

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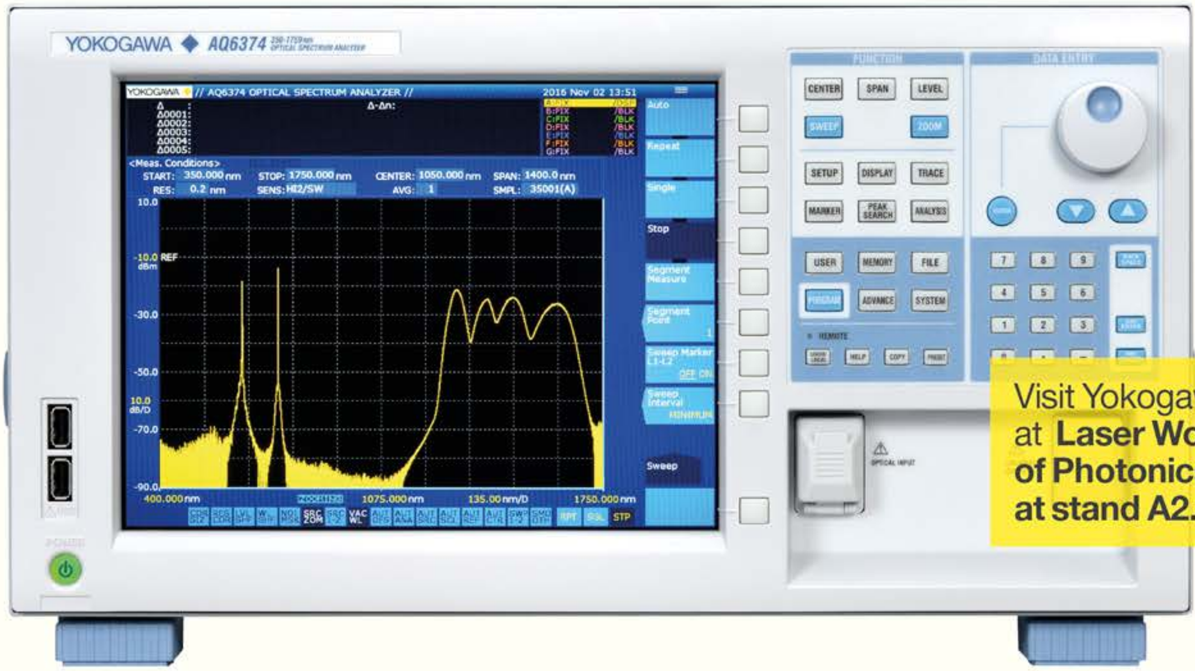

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4K televisions, which have four times as many pixels as the usual HD models, require realtime rates above 6 Gbps. Beyond broadcast-type applications or communication between base stations in the future 6G networks, wireless video transfer could be used for video transmission, or to rid operating theatres of the clutter of cables. The development of THz-range wireless communications will therefore require the development of terminal equipment (sources, amplifiers, detectors, antennae) that afford a power margin compatible with the link budget.

A range of different technologies have been or are in the process of being developed in laboratories to produce the first series of demonstrators, just as we saw with fibre-optic communication during early age in the 70-80's. Although both electronic and photonic solutions have been introduced, it is clear from the current state of the art (*Fig. 2*) that the main technologies behind these demonstrators have been taken straight from photonics, namely ultrafast InGaAs/InP uni-travelling-carrier photodiodes (UTC-PDs). Originally developed by the Nippon Telegraph and Telephone Corporation (NTT) in Japan for multi-stage optical reception at 40 Gbps, these photodiodes have been pushed to their very limits, making it possible to generate signals of up to 2.5 THz [4]. In the frequency bands appropriate for communication applications (around 300 GHz), levels in the order of mW have been reached [5]. Combining the tunable feature of optical beams in photonics with the photomixing technique (*Fig. 3*) makes it possible to transfer the techniques for generating vectorial optical fields developed in 2000-2010, and therefore technologically mature, to the THz range. Ultrafast photodiodes could therefore directly bridge the gap between fibre optics and high-speed radio networks (convergence of optical and radio technologies; see *Fig. 4*).

The advantage of techniques borrowed from photomixing is that they produce a very high modulation index of the optical wave, and thus of the THz wave generated by mixing. Moreover, if extra wavelengths are added, these techniques make it relatively easy to undertake multifrequency communication, which is extremely difficult to transpose to electronics. Coupling optical/THz techniques with THz receivers using Schottky

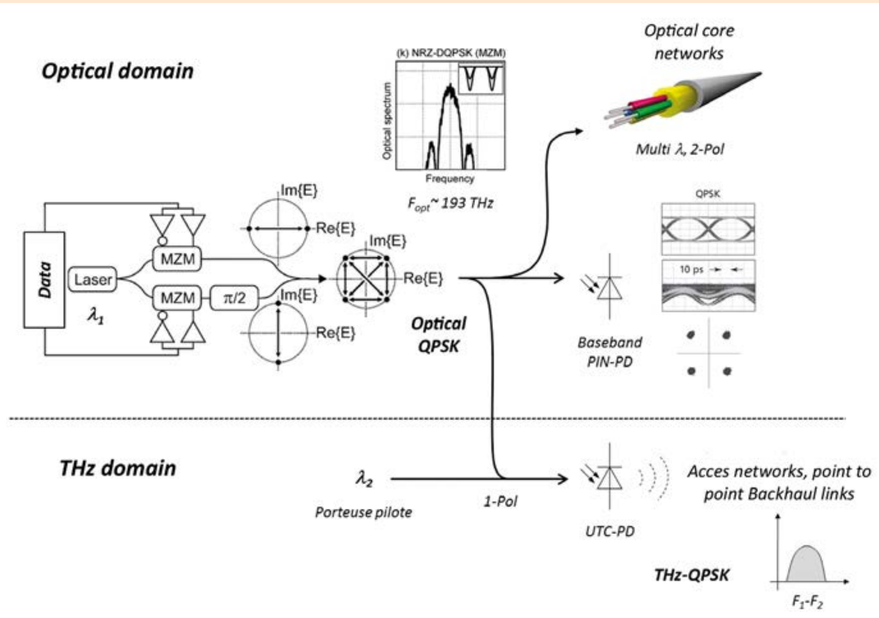

Figure 4. Convergence of optical and radio technologies: a modulated optical wavelength associated with a pilot carrier allows for the transition from optical vectorial modulation (phase coding, like quadrature phase shift keying (QPSK) where 4 phase states are used to encode the optical signal) to QPSK in the THz range.

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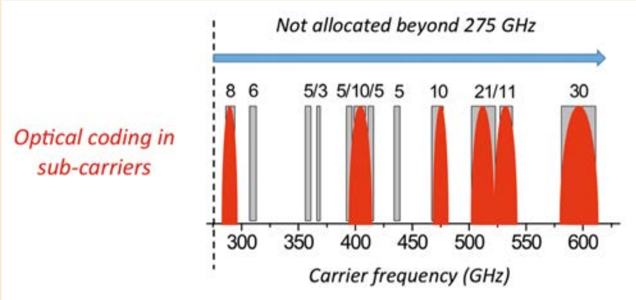

Figure 5. Possible frequency bands for THz communication (adapted from [9]).

diode mixers (originally developed for radio astronomy) produces data rates for THz carriers comparable to those of wavelength division multiplexing (WDM) channels over fibre which rely on a multi-color optical signal to increase the total capacity inside the fibre. For example, using technologies developed by NTT, a team in Japan led by THz communication pioneer Professor Nagatsuma reported real-time transmission rates in amplitude shift keying (i.e. digital amplitude modulation, ASK) amplitude modulation of up to 50 Gbps at 0.3 THz [6] – that is, approximately a thousand times current Wi-Fi! In France, researchers at IEMN have been working on very wide bandwidth communications, and ASK signals of up to 46 Gbps have been measured at 0.4 THz [7] and up to 32 Gbps using complex THz signals (quadrature amplitude modulation) over 25 meters [8]. As optical source phase noise requires corrective signal processing at the receiver end, complex signals are already being used to improve link spectral efficacy in the THz range, for even though there is a very wide available bandwidth, the presence of observation services (radio astronomy, meteorology) in this frequency range means that future allocations of THz channels will be in subbands, as illustrated in *Figure 5*. The use of coherent optical networks and flexgrids coupled with pilot carriers allows multispectral operation to be achieved in the THz range, as shown in *Figure 5*. 60-Gbps links operating at 0.2 THz [10] have thus been demonstrated. The race is now on to reach the 100-Gbps data rate, which should become a standard within the coming years for frequency bands above 275 GHz.

Technologies derived from electronics are also being developed. The first demonstrators were built using III-V components originally developed for radio astronomy [11,12], as well as high-electron-mobility transistor (HEMT) circuits [13]. It should, however, be noted that the highest rates were first achieved using emission technologies borrowed from photonics, taking advantage of the wide bandwidths associated with opto-electronic devices. As an example, a demonstration was reported at IEMN [8] for up to 32 Gbps transmission over 25 m at 385 GHz (*Fig. 6*), using high spectral efficiency. However, even if first links have been achieved 'out-of-the-lab', the limited available output power of photonic devices (currently around 1 mW at 300 GHz) will make the future of THz systems based on photonic transmitters may lie in a combination of solid-state amplifiers (e.g., InP-based heterojunction bipolar transistors (HBTs)) and photomixers. Moreover, the development of THz links could also benefit from recent advances in silicon photonics. For example, at 180 GHz, a Ge-based photomixer on an Si platform can exhibit an equivalent isotropic radiated power (EIRP) of more than -15 dBm in the 170–190 GHz band [14], with the high degree of integration associated with these technologies. As for the likelihood of achieving cheap, low-consumption THz transmission links in the future, CMOS technologies have also been considered, and the transmission of several Gbps at 130 GHz has already been achieved for indoor communications [15]. As with early MODEMs and early optical transmission systems, communication in the THz range holds out the promise of high performance and new uses over the next two decades. ■

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BACK TO BASICS: Computer-generated holograms

From the invention of the laser and early calculators to the very latest applications

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Diffractive optical elements (DOEs) have many advantages over conventional ones. For a start, they are generally lighter, take up less room, and have a wider variety of properties. They can also be used to fabricate hybrid elements that modify polarization, compensate for dispersion, and so on. Moreover, they are potentially low cost, as they can be mass replicated using manufacturing methods similar to those employed for semiconductor devices. It should therefore come as no surprise to learn that DOEs already have many industrial applications.

The rapid development of photolithographic techniques, and micromanufacturing in general, means that it is now possible to produce increasingly precise and complex DOEs, or phase masks. When these are placed in front of a light beam, they spatially modify the wave front to produce the desired light distribution.

There are hundreds of industrial applications for DOEs in areas ranging from optical telecommunications, lasers, anti-counterfeit solutions, microdisplay technologies and optical design, to industrial vision, lithography, biotechnology, and a whole host of gadgets.

For example, a red laser diode can be fitted with interchangeable DOE modules (red cylinder, *Fig. 1*) to create dot grids, concentric circles, lines, and so on. These types of tools are extremely useful for industrial vision and three-dimensional measures.

Spatial light modulators (SLMs), microelectromechanical systems (MEMs) and micromirror devices, or deformable mirrors, are also becoming increasingly diversified and efficient. All these DOEs provide local wavefront control and make it possible to modify light beams in real time. They are being used in a growing number of sophisticated optical applications.

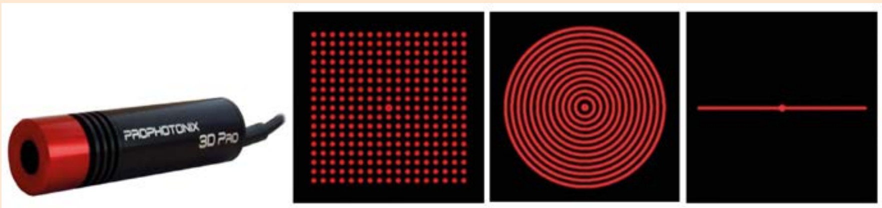

Figure 1. Examples of figures obtained with diffractive elements (www.prophotonix.com).

Before describing some of their recent and more spectacular research applications, we recall how these phase masks are calculated.

Digital holography, prehistory

First, we will travel back 35 years in time to the yellow corridor of Building 503 at Orsay University, where Institut d'Optique Graduate School (IOGS) students did their lab work. For generations of young SupOpticians, stretching back to the 1980s, one of the most memorable labwork sessions was undoubtedly the one on computer-generated holograms (CGHs). When I was appointed in 1992 to teach these practicals at the institute, I soon found that this experiment was an endless source of fascination for our engineering students. Back then, the holograms were calculated using a very imposing HP 1000 minicomputer! If I remember rightly, students would feed in a 512 × 512 binary table, in other words a black-and-white image measuring 512 × 512 pixels, which the faithful HP 1000 would then store in its memory, and calculate its 2D fast Fourier transform (FFT). Using Lohmann's coding scheme (to which we will return later), the 2D FFT allowed the computer to represent the binary table as an array of 512 complex numbers. The resulting Lohmann hologram was printed in the building's ground-floor computer room. Printed? Well, in reality, the *printer* was probably

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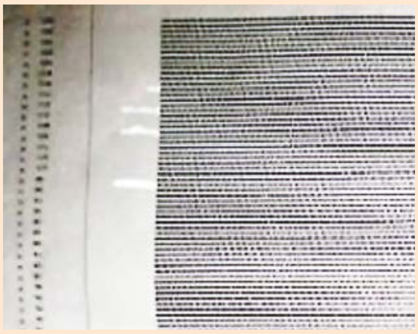

Figure 2. A Lohmann hologram, probably printed in around 1985 at the Optics Institute.

an HP plotter. *"A machine that made as much noise as a pneumatic drill"*, recalls Jean-Paul Hugonin, who ran the same type of practical with first-year PhD students. *"We might as well have been carving out the holograms with a chisel. It was like something out of the Stone Age"*, adds Thierry Avignon, who always went round before each session checking that none of the plotter's black pens had dried out! Jean Taboury, who was director of studies back then and jointly in charge of the physical optics lectures with Pierre Chauvel, has sent me a photo of a CGH dating from this heroic period (*Fig. 2*).

Once they had printed out this sheet containing apparently randomly distributed tiny black squares, the students then had to photographically reduce this hologram. This involved taping the A4 sheet to the wall, shining old studio lights on it, carrying out highly precise manual focusing, and taking a dozen or so photographs of this sheet, adjusting the diaphragm aperture and shutter speed to obtain a 24 × 36 mm negative with as much contrast as possible. To achieve sufficient resolution, we used an excellent 50-mm fixed focal length lens mounted on a Canon camera body.

Then came the moment that was the most tense and nerve-racking for the students, when they had to develop the film. After taking out the 50-ASA black-and-white film (always very fine-grained, to ensure the best resolution) in the dark room prepared beforehand by Marie-Thé Plantegenest or Thierry Avignon, they would have to roll it onto a reel (no easy task) and dip it in a whole series of baths. Only then could they start feeling positive about the negatives! This operation was not always successful, and the poor students sometimes had to start all over again. For many of them, this was undoubtedly a lastingly traumatic experience. It must have been so for Riad Haidar, editor-in-chief of *Photoniques*, but also an alumnus of SupOptique who presumably has spent some time in this quaint dark room back in 1999, otherwise why would he have commissioned me to write this article so many years later?

But let us get back to our home-made CGH. Once the film had been developed, everyone could relax, and the students would take a break while the film dried in the old grey cupboard housing the hot-air dryer. Once the film was ready, the best method was to carefully cut it into individual photos and surround the reduced hologram on the slide with thick black tape to ensure that the light passed through – and not around – the hologram.

At last came the reward, when the CGH, or more accurately the photo-reduced negative of the hologram (*Fig. 2*), was placed in a convergent HeNe laser beam, and an image such as this one (*Fig. 3*) appeared in the convergence plane, that is, the image plane of the beam waist.

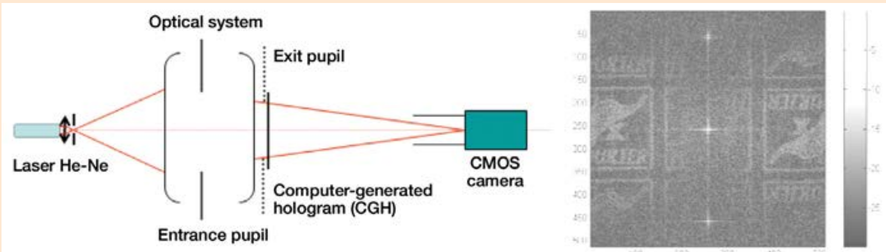

Figure 3. Reconstruction of a Lohmann hologram using an optical bench and bicorn image captured by the camera.

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Figure 4. The Cheshire cat (128 × 128 pixels) and a small part of its CGH.

Indeed, at the end of his annual lecture on Joseph Fourier to first-year students at École polytechnique, Philippe Grangier, a friend since our student days at ENS Cachan, would present this experiment to illustrate the FT. Each year, in the month of June, Thierry Avignon and Cédric Lejeune would take the legendary optical bench by car from the Optics Institute building to École polytechnique and set it up in the lofty Henri Poincaré lecture hall. And when Philippe revealed the result of the optical FT of a hologram of the Polytechnician's bicorn hat (*Fig. 3*) on the panoramic screen, there would be a rapturous round of applause for the experiment, Philippe's lecture, the genius of Joseph Fourier and, I assume, the famous bicorn.

Fourier's optics

For it is indeed FT that we are talking about here, as the illuminance in the image plane of a point source (coherent lighting) is an example of Fraunhofer diffraction, the key being to observe at the point conjugate to the point source. The wave amplitude in the image plane (camera plane) can therefore easily be calculated from the wave amplitude in the pupil using 2D FFT. Conversely, to obtain an image of the object of your dreams in the camera, however, you simply need to calculate the FT of that image and modulate the wave in the pupil plane through transmittance proportional to this 2D FFT.

Simply? That is precisely the problem, as transmittance is a 2D complex matrix. You therefore need an SLM that can modulate amplitude, and an SLM that can modulate phase, in order to give the wave in the pupil the right phase and amplitude distribution, and thus produce the image of your dreams in the image plane.

You might think that a black-and-white negative cannot provide phase modulation, but the bicorn on the large screen says otherwise. CGHs therefore do modulate the wave phase. But how do we get round the absence of a phase modulator?

The secret of the Lohmann hologram

Denis Gabor's brilliant invention of holography in 1947, which he hoped would improve the resolution of electron microscopes, may provide the key. To conserve the phase of an optical wave (object wave), this object wave must be made to interfere with a reference wave. Once the interference fringes pattern has been printed on the hologram, we can reconstruct the object wave simply by illuminating the hologram with the reference wave.

The first sentence in the acceptance speech given by Denis Gabor 24 years later, when he was awarded the Nobel Prize in 1971 for his invention of holography was as follows [1]:

"I have the advantage in this lecture, over many of my predecessors, that I need not write down a single equation or show an abstract graph. One can of course introduce almost any amount of mathematics into holography, but the essentials can be explained and understood from physical argument."

Following his example, can we indeed explain without a single line of calculus the secret of Lohmann's hologram, which he set out in an article

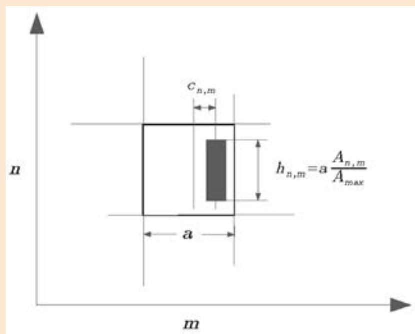

Figure 5. The phase detour illustrated on a square pixel with sides of length α, at the position (n,m). The height $h_{n,m}$ of the rectangle is proportional to the amplitude of this pixel of the FFT $A_{n,m}$. The displacement of the rectangle $c_{n,m}$ is proportional to its phase.

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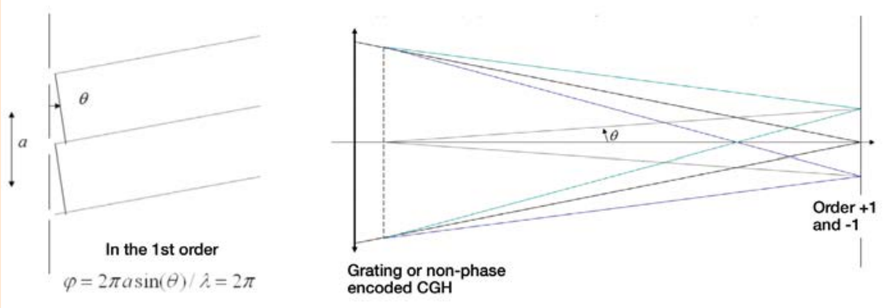

Figure 6. Case of a non-phase encoded CGH (equidistant white rectangles). The diffraction orders are obtained from a Foucault test card pattern transmittance.

published in 1967 [2], entitled "Binary Fraunhofer Holograms, Generated by Computer". This secret is the so-called detour phase method that Lohmann had described a year earlier [3]. In his article he wrote: *"There are three possibilities to influence the phase of a light wave: retardation while traveling through a dielectric, phase jump at reflection, and detour phase."*

We should say first of all that even though the CGH provides a flat image (and not a 3D one), it is still a hologram, as it provides a means of phase encoding.

Here is a typical hologram that can be produced with this method (*Fig. 4*). You will notice that I have chosen a cat – not necessarily Schrödinger's cat, both dead and alive at the same time, even if its hologram is reminiscent of a quantum cryptography system. In actual fact, it is a Cheshire cat, which can appear and disappear at will – an ability that greatly amused Alice in her *Adventures in Wonderland*.

Each tiny white rectangle encodes one of the pixels in the cat's 2D FFT (128 × 128 pixels) (*Fig. 4*), based on the following rule:

- the rectangle's surface area is proportional to the amplitude of the corresponding complex number;
- the rectangle is horizontally displaced relative to the pixel's centre, this displacement being proportional to the phase of the corresponding complex number.

Amplitude coding is easy enough to understand, as the amplitude of the wave transmitted by each rectangle is proportional to the surface of the tiny transparent rectangle on the film. Phase coding is slightly more subtle. If the phase is zero for all the pixels, all the rectangles will be vertically aligned, and the CGH's FT will only produce a point at the centre of the image (zero diffraction order) and horizontally aligned points (including ±1st diffraction orders). If we obtain a +1st order point in the direction θ, it is constructive interference, and the waves from two successive white squares will therefore be in phase (the phase is equal to 2π) (*Fig. 6*).

If, on the other hand, the rectangles are horizontally displaced relative to the centres of the pixels, the phase of the waves from two successive white squares will be proportional to the distance between these squares (*Fig. 7*), and we will obtain a picture of the cat centred on the direction of the +1st order. In -1st order, we would, of course, obtain a symmetrical image of the cat, as we would have encoded a phase with the opposite sign! The FT of the conjugate of an object yields a symmetrical image, as we can clearly see for the bicorns in *Figure 3*.

In reality, there are other ways of making our cat appear. One method consists in performing the FT of an image that is symmetrical in relation to its centre (*Fig. 8*), in which case the 2D FFT is a matrix of real numbers, the phase is zero, and the white rectangles therefore do not need to be displaced.

Lastly, we have said nothing about a method that can be systematically used, whereby a random phase is added to the binary object before calculating its 2D FFT, in order to achieve uniform amplitude in the Fourier plane (*Fig. 9*). This random phase has no impact on the reconstructed image, as the human eye and the camera (along with any other optical detector) are sensitive to the squared modulus of the wave, not its phase. The idea for this particular method, like others, comes from what we normally think of as holograms, and it does not work for objects with low light scattering. The wave from the object has to be spread across a large area of the hologram, so we place a finely ground glass plate in its trajectory, just in front of the object.

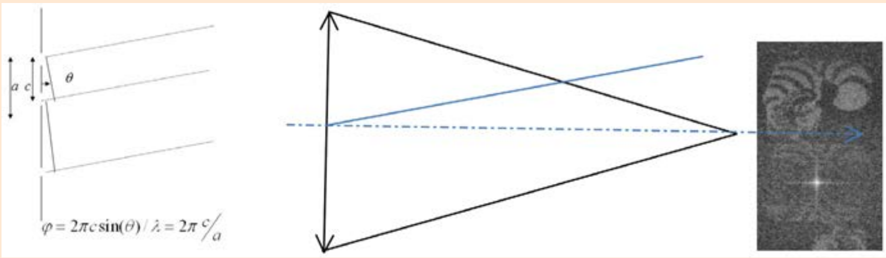

Figure 7. Case of a phase-coded CGH (white rectangles displaced proportionally to the phase) and result of the optical Fourier transform.

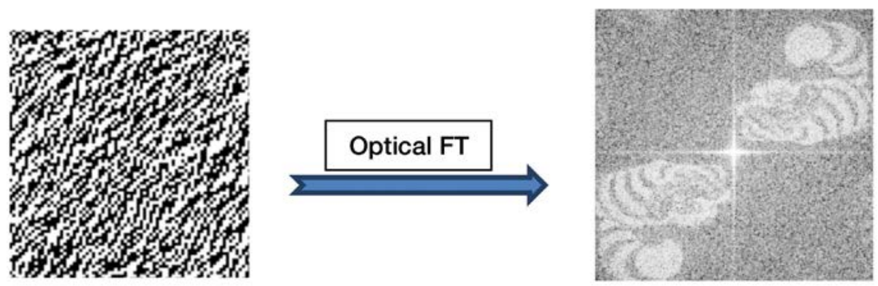

Figure 8. Binary hologram of symmetrical cats and reconstruction by the optical FT.

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Digital holography today

Even though the Labwork Department has changed its name to Experimental Teaching Laboratory (LEnsE) and is now led by Fabienne Bernard, a colleague of mine who joined the IOGS in 1996, and even though the labwork session is no longer officially about CGHs, but about simple diffractive elements, it is still run for 3rd-year students, who continue to be amazed when they see cats appearing on the walls. It now takes no time at all to produce a CGH. The holograms are calculated with a short MATLAB programme on a standard PC, and a laser printer then transfers them onto transparencies. We also study holographic aberration correction, as CGHs or diffractive devices are still used to measure aspherical surfaces or correct aberrations.

These CGHs, with a spatial amplitude modulation of the transmitted wave, are highly inefficient. The illumination is inevitably at its greatest in the axis of the image plane (zero diffraction order) and orders +1 and -1 are far darker.

As I indicated at the start of this article, technological advances mean that extremely accurate phase masks, or DOEs, can now be mass-produced. The images in *Figure 1* show that these DOEs allow to obtaining almost no zero order. The good news is that amplitude modulation is not required. Phase modulation is all that is needed to achieve any binary light distributions. The phase can be retrieved

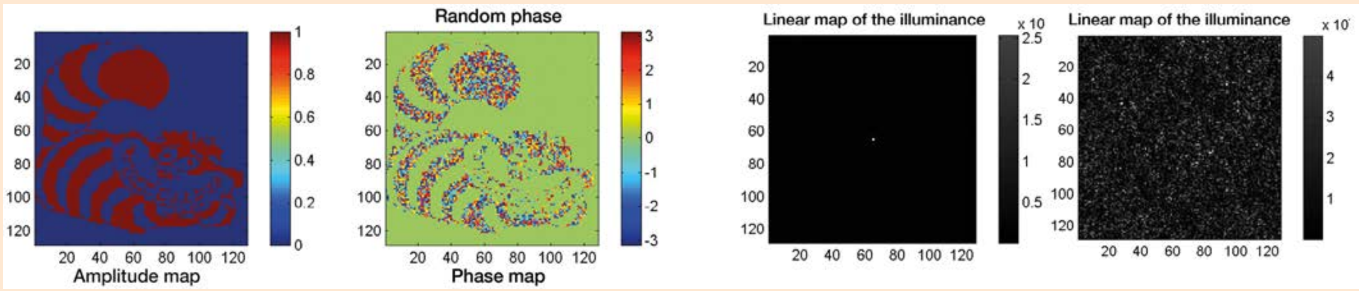

Figure 9. Solitary cat, and cat multiplied by random phase (left); FFT of the cat without and with random phase (right).

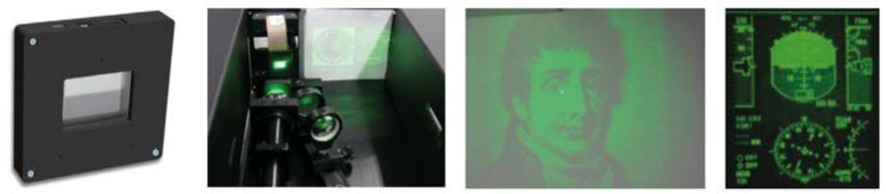

Figure 10. SLM Holoeye and portrait of Joseph Fourier by Julien Léopold Boilly (www.holoeye.com).

using the Gerchberg-Saxton iterative 2D FFT algorithm [5], which is extremely easy to programme in MATLAB. Moreover, some phase modulators can now be configured to operate at video rate (real time). These are liquid crystal display (LCD)-based SLMs, which have been used since the early 2000s in mobile phones and video projectors to modulate intensity. If a different configuration of the input and output polarizers is used, these same devices become phase modulators. Their advantage over DOEs is that they allow the CGH to be modified so that, for example, vehicle speed can be displayed on a dashboard and, just 50 ms later, the portrait of Joseph Fourier (*Fig. 10*).

LEnsE's recent acquisition[1] of an SLM Holoeye enabled master's student Ivan Fernandez de Jauregui Ruiz to demonstrate a superb experiment involving the selection of spatial modes injected into a weakly multimode fibre, as part of his Erasmus Mundus programme.

This particular type of SLM is also widely used in microscopy (e.g. most recently in structure illumination methods, bringing a twofold improvement over the diffraction limit) or in optical tweezers that can trap and handle cells or particles (*Photoniques* **66**, July-August 2013, "La pince optique" by Jean-Pierre Galaup).

SLMs can also be used to trap atoms, as demonstrated by Sylvian Ravets, a member of the Quantum Optics group of the Charles Fabry lab. When Sylvain reprised research carried out with the assistance of LEnsE back in 2004 [5], as part of his PhD supervised by Antoine Browaeys [6] he successfully designed microtrap arrays for single atoms with varied and complex geometries (*Fig. 11*).

To end this article, which gave me such pleasure to write, I will simply quote the sentence that SupOptique students find on the LEnsE computer screen each time they quit one of *my* MATLAB applications: *"Fourier optics is beautiful. Thank you and goodbye!"*

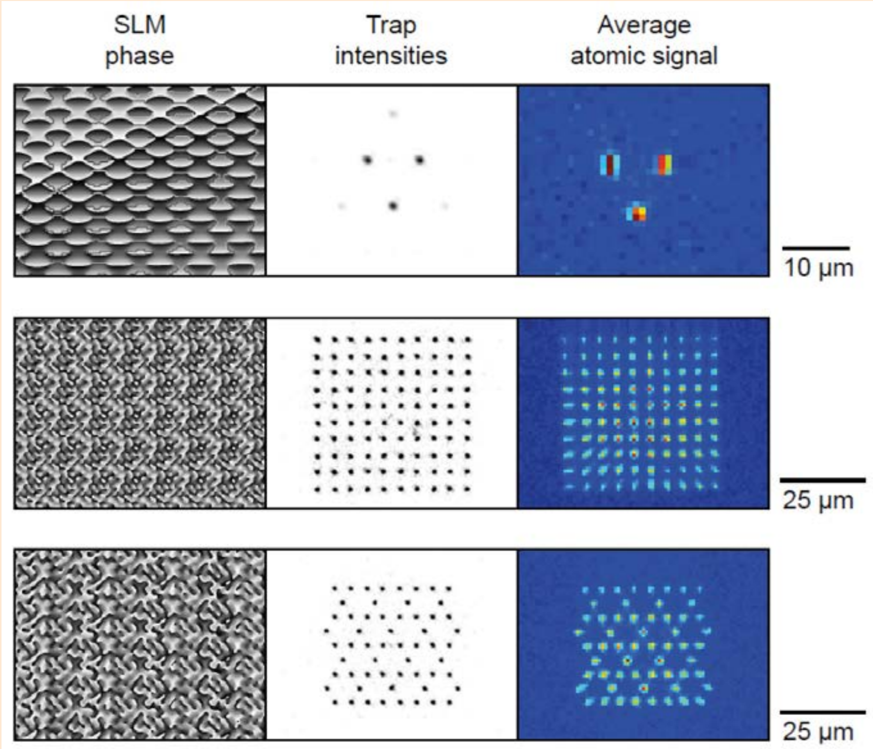

Figure 11. Examples of microtrap arrays (left: hologram; centre: CCD images of traps; right: mean of 1000 fluorescence images of single charged atoms in the traps) (thesis defended by Sylvain Ravets on 18 December 2014 at IOGS and [6]).

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BUYING a positioning system

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A positioning system consists of a mechanic or mechatronic motion device for linear, rotary or combined motion plus motion control electronics. It moves objects with micro-, nano- or even sub-nanometer precision. Many photonic applications and optical devices or inspection systems require high positioning accuracy, especially in microscopy, nanolithography and interferometry.

Today's microscopes are often equipped with piezo stages that offer up to six degrees of freedom, thus allowing for rapid, high-precision scanning. For example, an objective or sample scanner based on piezoelectric actuators can provide high-speed Z motion for fast and throughput optimized autofocusing tasks with high precision.

The exact speed and accuracy depend largely on the choice of control electronics and how they match in terms of parameter setting. This choice must be made in consultation with the user.

Positioning systems can be divided into two main families, according to their degree of accuracy (micro- or nanometer range).

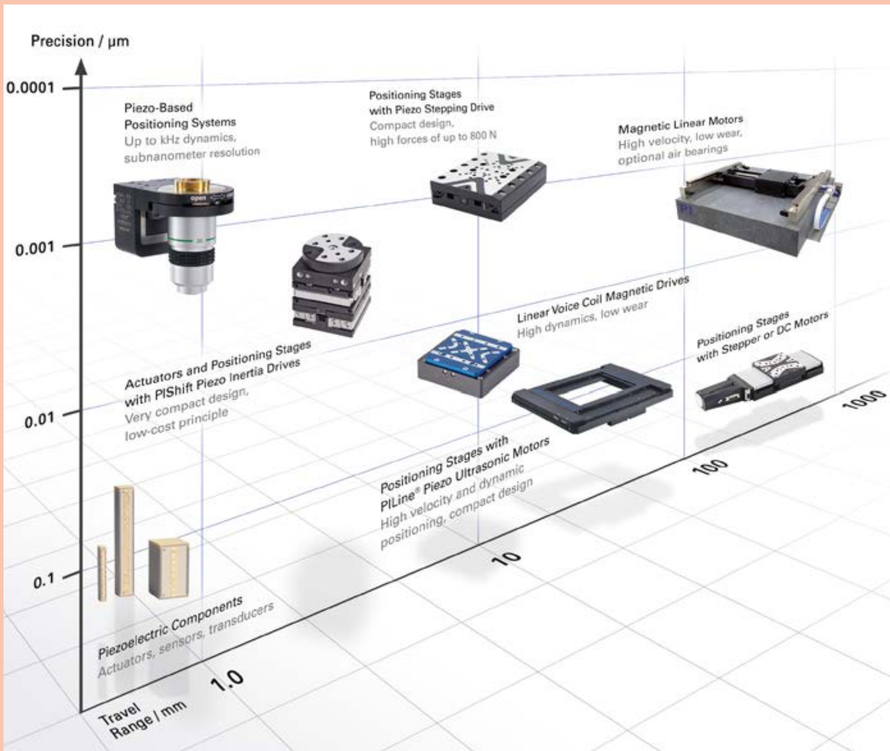

Figure 1. Product Roadmap. The choice of the drive system strongly depends on the demands for travel range and resolution.

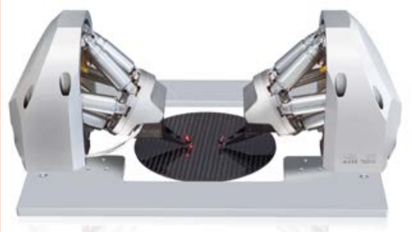

Figure 2. Multi-channel fiber alignment system for silicon photonics device testing.

Micropositioning systems

Micropositioning systems offer travel ranges of between several millimeters and several meters, and are accurate (e.g. for repeatability) in the range of 0.1 to 10s of microns. Linear or rotary stages can be fitted with a range of drive and bearing concepts such as DC motors or stepper motors with spindle drives, magnetic direct drives or piezoelectric drives. In terms of precision, mechanical guiding systems such as ball bearings are sufficient.

When choosing a micropositioning system, a large number of factors need to be taken into consideration. They generally include the number of degrees of freedom, available travel range, resolution or minimum motion increment, positioning repeatability, or accuracy. Precision criteria will dictate the type of position sensor that is considered (e.g. linear encoders) and the guidance quality to be selected (e.g. flatness, pitch and yaw, wobble and eccentricity). For many applications, it must be possible to parameterize the speed of travel. Lastly, the nature of the system's components determines both its lifespan and the environments in which it can be used (e.g. vacuum, magnetic).

Nanopositioning systems

With nanopositioning systems, the precision is even better than with micropositioning systems; they provide repeatability in the range of 10 down to 0.1 nanometers. In this class of precision, the choice of system components is limited! As mechanical friction needs to be avoided, possible drive concepts are magnetic direct drives and piezoelectric actuators. Recent developments in piezoelectric motors and control electronics mean that it is also possible to have piezo motion with travel ranges of up to several millimeters at nanometer precision. Besides the proper drive, stages for nanopositioning use flexure bearings for small and air bearings for large travel ranges. Non-contact sensors are either optical or capacitive ones.

Many factors need to be considered when choosing a nanopositioning system, and they depend directly on the final application. If, for example, the main requirement is speed (i.e. dynamics), it requires a system with a high resonant frequency and high-bandwidth electronics. The setting of these dynamic parameters is therefore crucial – as is the payload the system will be expected to bear.

By contrast, if the main requirement is extremely high precision or resolution, it is important to opt for a system with one or more position sensors (capacitive or strain gauge) and to adjust the control electronics parameters according to the nature of the sensor(s) and the payload. The choice of a nanopositioning system should therefore always go hand in hand with the choice of control electronics. Only an appropriate combination of the two will guarantee the best possible performances in terms of the target application.

Figure 3. Piezoelectric motors are built into miniaturized positioning stages – the image shows versions with a width of only 22 mm. Stages like these are used inside micro manufacturing applications and for photonic alignment tasks. They are also available for ultra-high vacuum applications, where space is limited.

Selection criteria

Positioning systems have many technical parameters. Here, we will limit ourselves to those that concern actuators and positioning stages or systems, leaving the control electronics aside.

The accuracy of a positioning system is defined as the difference between the actual versus desired positions.

- Resolution corresponds to the smallest measurable position increment. It is important to distinguish open-loop resolution from closed-loop resolution, which is achieved using a position sensor coupled with a controller.
- Repeatability is the ability to return to a given position from any other position. It is limited by hysteresis and backlash.
- Speed: piezoelectric actuators provide sub-millisecond response times, but it is important to define each system's functional requirements (*XY scanning*, description of periodic patterns).

Attention also needs to be paid to the other parameters, namely resonance frequency (stiffness), load (maximum weight the system can withstand), maximum travel range (from several micrometers to several hundred millimeters), compactness (system's overall volume), and lastly the ability to operate in a vacuum or at cryogenic temperatures. ■

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ARDOP	Eksma Optics	**Mathias Le Pennec** +33 1 69 63 26 12 – mathias.lepennec@ardop.com

Raman amplifier

LEA-Photonics is proposing CW multi pumps Raman amplifier for wideband DWDM. Available in very compact modules or in a highly-developed 1U rack with SNMP supervision option, they are optimized to amplify DWDM signals over the C-Band with flat gain. The Raman amplifiers provide high output pump power using wavelength-combined 14xx nm pump laser diodes. They also incorporate automatic power reduction (APR) when the output fiber is not properly terminated or optically disconnected. Finally, the pump power ratio is tunable for gain optimization.

www.lea-photonics.com

Piezo stage

Micronix USA is now able to offer closed loop miniature piezo stages and a matched controller at the low price of typical low cost open loop stepper systems. Starting at 20mm × 18mm × 10mm (l × w × h), the new low cost PP-18 offers cross-roller bearings to assure high stiffness and is driven by our patented multi-phase piezo motor resulting in high speed (> 2 mm/s) and high blocking force (> 1.5 N). A linear encoder with 40nm resolution is standard on all PP-18 stage to ensure repeatability.

www.oceanoptics.com

Mid-IR supercontinuum laser

Le Verre Fluoré and Leukos have polled their respective expertise in fluoride glass and in supercontinuum generation, to deliver an innovative Mid-IR supercontinuum laser. This solution, the SM-MIR, covering up to 4.1 µm, delivering more than 700 mW, is already available at Leukos.

www.leukos-systems.com

Calibration light source

Gamma Scientific has expanded their family of SpectralLED tunable LED light sources for camera and image sensor calibration with a new system having a substantially larger output port, as well as increased output uniformity. Specifically, the new SpectralLED RS-7-2 mates up to four LED light source engines together with a 1 meter sphere that includes a 300 mm output port (other sphere and port sizes are available, as well). The result is a calibration light source for very large area detectors and large field of view cameras that delivers significantly higher brightness and approximately one order of magnitude higher radiometric stability (<0.1%) and wavelength accuracy (0.25 nm) than any competing product.

www.gamma-sci.com

Picosecond laser

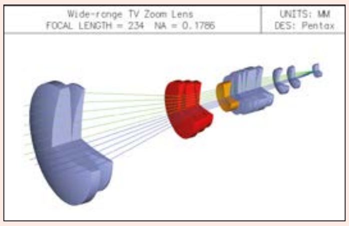
The PiXea is a stand-alone picosecond laser dedicated for industrial and scientific applications in the 375 nm to 2 µm spectral range. This very-low timing-jitter laser performs very sharp pulses width down to 20 ps with a continuously tuning of the repetition rate up to 100 MHz and a peak power up to 500 mW. The modern interfaces of the PiXea make it an essential tool for any accurate time analysis, characterizations and laser seeding.
www.aureatechnology.com

Laser combiner

Toptica's NEW iChrome CLE, includes four laser sources with output power up to 20 mW max. All integrated wavelengths are controllable via a unified user interface (analog and digital inputs, as well as RS232 and Ethernet). Providing 405 nm, 488 nm, 561 nm et 640 nm, iChrome CLE is an excellent laser light source for microscopy, especially optimized for confocal microscopy. The combinaison of these colors enables excitation of the majority of popular fluorophores with only one fully integrated device. Toptica also provides a ready-to -use, user friendly control software.
www.optonlaser.com

Optical design software

Lambda Research has released OSLO 7, which contains significant updates and enhancements. OSLO 7 includes Windows 10 support, improved Zemax and CodeV import, and STEP export that supports all surface types as well as updated Ohara, Hikari, Hoya, and Schott glass catalogs direct from the manufacturer. In addition to classical lens design features, OSLO (Optics Software for Layout and Optimization) is used to simulate and analyze the performance of optical systems by combining advanced ray tracing, analysis, and optimization methods with compiled macro language.



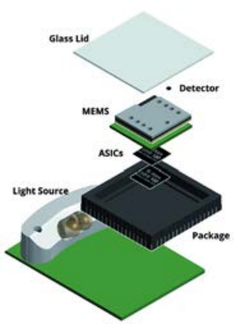
www.lambdares.com

InGaAs camera

First Light Imaging complete its Infrared range of scientific cameras with C-RED 2, a very compact high-performance InGaAs camera. C-RED 2 outperforms the capacities of its 640 × 512 InGaAs 15 µm pixels high resolution sensor, offering a breakthrough frame rate up to 400 images per second full frame while being ultrasensitive: from 10 to 30 electrons read out noise at full speed. The sensor embeds an electronic shutter with an opening delay lower than 1 µs. C-RED 2 is designed for astronomy, bioimaging or industrial applications, in very low light conditions and in any environment.
www.first-light.fr

Micro-spectrometers FT-IR

Si-Ware Systems (SWS) introduces the first integrated micro-spectrometer for broad industrial and consumer use. Delivering the same functionality as conventional "bench-top" spectrometers in labs, the integrated NeoSpectra Micro brings to end-users the ability to immediately quantify composition, detect impurities and ascertain quality, speed analysis of samples from days to minutes without the need for offsite lab verification.

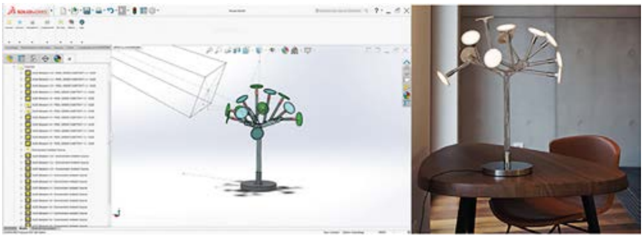


http://mesure.optoprim.com/

❙ Ultra-black coating

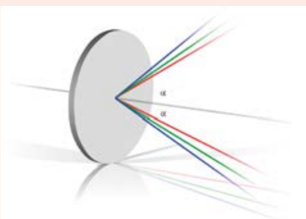
SBIR and Acal BFi announce a new ultra-black surface coating technology that improves infrared emissivity in the mid-wave-infrared (MWIR) and longwave-infrared (LWIR) spectral wavelengths. In the MWIR (3-5 µm), emissivity is > 99.8% (± 0.1%); in the LWIR (8-12 µm) emissivity is > 99.5% (± 0.15%). Developed for space-borne imaging applications, Vantablack surface coating material offers exceptional IR absorption and excellent thermal, mechanical and environmental stability. The new material was recently deployed on an Earth-observation satellite.
www.acalbfi.com

❙ Lighting simulation



SPEOS for Solidworks, the brand new integration of SPEOS into a CAD platform, is now available to accompany users in their lighting simulation. The use of the software has been facilitated for non-expert users. This new version also gives Solidworks' users access to the core system of other OPTIS technologies, giving users access to the brand new Optis HPC technology. The new software simulation results are now virtual reality-ready and can be reviewed with any virtual reality helmet and in any virtual reality center.
www.optis-world.com

Triple mirrors



Laser Components developed a new coating process for so-called triple mirrors that makes it possible to apply this complex layer design in one pass. Coatings for three wavelengths used to have to be manufactured in two passes. The new method not only results in higher specifications, but it also has the additional advantage of a shorter duration of production. Furthermore, the new applied coating unit contains more substrates than before, allowing larger amounts to be produced. This positively affects the unit price. Triple mirrors are used, for example, in Nd:YAG laser systems that emit at the fundamental wave-length 1064 nm (IR) and have harmonic waves at 532 nm (green) and 355 nm (UV). Customers can pick their wavelengths individually – many combinations are possible.
www.lasercomponents.com

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100 W fs laser

Amplitude introduces Tangor, an industrial femtosecond laser with average output power in excess of 100 W. Tangor produces 400 fs pulses, peak powers greater than 500 MW, single-shot to 2 MHz repetition frequencies, and superior beam quality. By combining a fiber seeded oscillator with a crystal-booster amplifier, Amplitude has produced a hybrid fs laser platform that delivers industry leading average power with high pulse energies. These innovations, combined with high pulse repetition rates, burst mode operation, and pulse synchronization allows for straightforward integration in complex scanning and beam delivery systems. The addition of harmonic generation into the green and ultraviolet allows for processing of a wide range of complex materials.
www.amplitude-systemes.com

Fiber-coupled modulators

Fiber-Q devices enable high speed optical pulse picking at infrared wavelengths for all-fiber laser systems. They offer high extinction ratio, low insertion loss, and excellent stability in both polarization maintaining (PM) and non-PM formats at modulation frequencies up to 80 MHz for visible and infrared wavelengths. Compact, low-profile package allows integration into all-fiber and OEM systems, including medical laser systems.
www.goochandhousego.com

Femtosecond lasers

Coherent has extended the performance of their Monaco series of industrial-grade femtosecond lasers by increasing their adjustable pulse repetition rate to a maximum of 50 MHz. A new high energy Monaco provides up to 60 μJ/pulse in the near infrared (1035 nm), or, optionally 30 μJ in the green (517 nm). These improvements provide enhanced performance in precision materials processing applications, particularly for delicate and/or tough materials, and also deliver increased frame rates in demanding multiphoton microscopy imaging applications. All Monaco lasers produce a high quality (M2 < 1.2) beam, enabling tight focusing for high brightness and high spatial resolution. Additionally, the pulsewidth can be user set from under 400 fs to over 10 ps.
www.coherent.com

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