Spotlight on photonics.

TECHNOLOGY ROADMAP

of Photonics in Austria 2021 – 2027



PHOTONICS AUSTRIA

In the light of the future.

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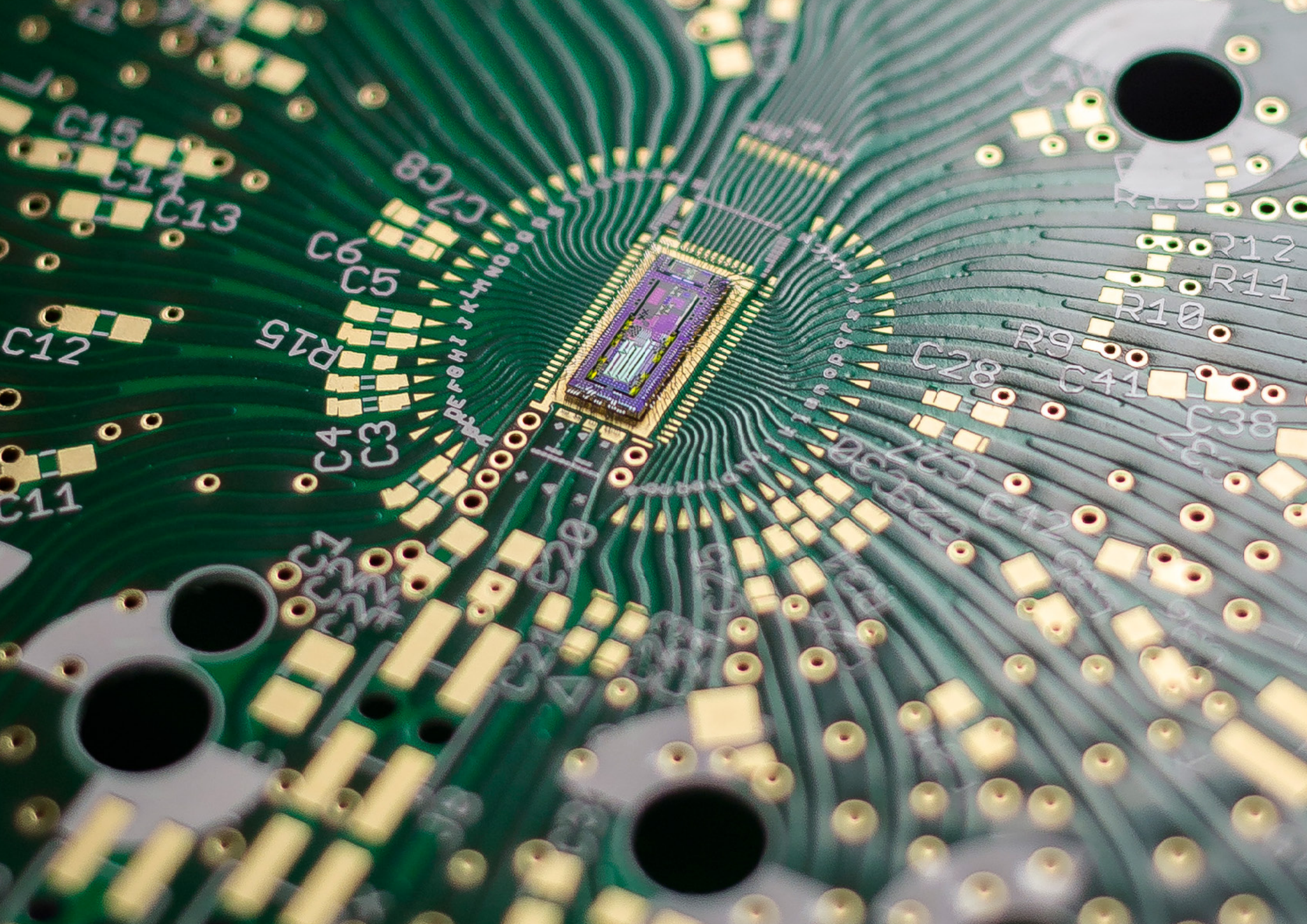
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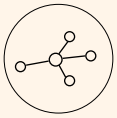
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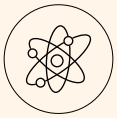
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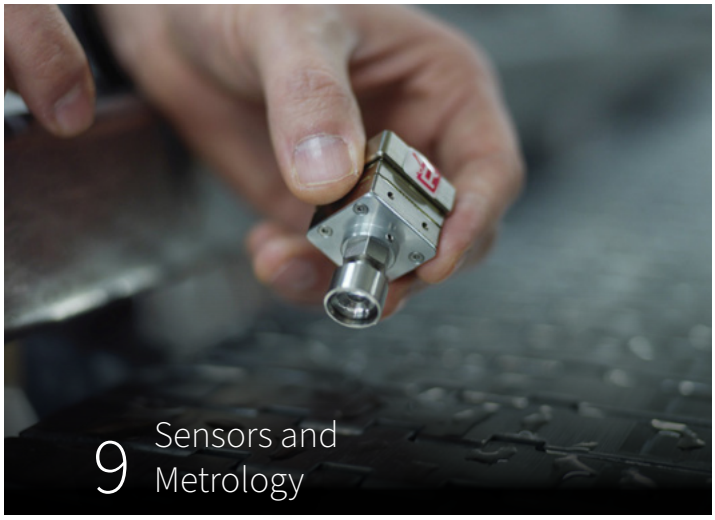


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Preface

VERENA VESCOLI,
SENIOR VICE PRESIDENT R&D AMS

Photonics - the key technology of the information age

A multitude of data – text, sound, images and videos, speech or sound – are generated, captured, distributed, processed and stored worldwide. Conventional technologies are reaching their limits. Photonics, in ICT a functional symbiosis of electronics and optics, is the ***key to technologies of the future*** that will be able to provide innovative and sustainable solutions for our society and environment.

The combination of solid-state physics, semiconductor technology and optoelectronics is the starting point for innovative and extraordinary technologies of the future. In addition to optical information transfer and photonic networks, photonic integrated circuits (so-called PICs), are among the technologies that will enable the realization of complex sensor systems in a more compact and resource-efficient way, while maintaining or improving functionality compared to discrete integrated components. ***Higher system complexity in combination with reduced form factor at lower manufacturing costs*** – this is the focus of research and development activities in photonics. These pave the way for highly innovative solutions: Areas of application can be found, for example, in the fields of lively and dynamic visualization, intelligent lighting that is precisely adapted to human needs and in the mobility of the future. Only photonics and the heterointegration of photonic and electronic components enable electronic systems with novel properties and functionalities.

The "More Moore" technology paradigm of miniaturization, which has dominated recent decades, is now being extended by "More-than-Moore" and "Beyond-Moore". Thanks to photonics, future technological progress can be ***decoupled from steadily growing energy demand***. For example, photonic circuits will enable cloud computing at a fraction of today's energy requirements. By doing so, it will be possible to process the projected amounts of data in the future. Sensors based on photonic devices will be able to measure people's vital functions and detect pathogens at any time and any place. On the one hand, this will revolutionize medical diagnostics, and on the other hand, in view of pandemics and an aging society, it will increase the ***quality of life*** of every individual in society.

The Roadmap for Photonics builds upon the strengths of the Austrian photonics sector, increases its competitiveness and points the way to a better and more liveable future. Photonics provides sustainable technologies for social and technological megatrends such as digitalization and communication, healthcare, climate protection and security. Photonics is thus becoming a significant driving force for economic growth, employment and sustainable development of society in the heart of Europe and beyond.

The close partnership between the photonics industry and academic research is essential for the successful and prompt implementation of this roadmap. The partners in Austria address all areas of photonics, ranging from high-energy short-wavelength radiation in the extreme ultraviolet and visible light to the infrared and far-infrared spectral range. ●



Mobile devices as an integral part of our lives are excellently suited to control smart Human Centric Lighting, which has a great impact on our mood, well-being and health

Photonics as a key technology

What is light and how can we use it?

Light is an elementary phenomenon. It is the foundation of life and surrounds us everywhere, at all times. Most people take this for granted and forget that multitudes of things in daily life are enabled by light. It allows us to see colours, but it also transmits energy so that we feel heat. Plants need light for photosynthesis while in other creatures, such as humans, it influences hormone release and causes a feeling of satisfaction.

Due to its versatile properties and various applications, humanity began to use light for technical purposes as well. This laid the foundation for photonics. Technological progress developed Photonics even further and in turn opened up new possibilities.

Today, ***photonic applications are part of many everyday*** devices such as smartphones, screens or lighting in general. Light has also become an indispensable tool for industry and medicine. Especially since climate and environmental protection, in connection with the expansion of mobility, energy, communication, safety and health, pose major challenges for modern society.

Topics such as energy and resource conservation are becoming the cornerstone of the latest technical achievements. Applications, which are not environmentally compatible, are currently hardly justifiable. This is where photonics plays a key role. Photonics enables more efficient and sustainable processes and a reduction in waste and emissions. Thus, photonic technologies have considerable potential for the future, which could make a decisive contribution to improve the quality of life of future generations.

What is photonics?

Photonics deals with light and its technical use. The term photonics is composed of the term photon and the suffix of electronics. Today, this includes optical technologies that are used to generate, amplify, transmit, control and measure electromagnetic radiation. Photons are the smallest discrete energy packets of light. Electrons interact with photons, resulting in the interface with electronics.[1,2]

The importance of photonics for the European economy

Photonics plays a central role in Austrian and European technology development as an explicit ***Key Enabling Technology***, and is developing at a rapid pace. As a result, photonics provides a rich source of technological developments and commercial exploitation opportunities, making it an essential factor in the industrial economy.[3]

The global ***photonics market was 690 billion € in 2019*** with the European market at 103 billion € (15 %) and an average growth rate of 7 % (2005-2019), which is three times the rate of European gross national product and also higher than the growth of comparable high-tech sectors (e.g. microelectronics: 4 %). 390,000 jobs could be directly attributed to the photonics segment in the EU in 2019[4], with high-tech sectors and high-value products dominating. In many market sectors, the market leaders come from Europe. Some of them are from Austria, although they sometimes can be described as "hidden champions".

The market share of European companies in sub-segments is considerable and ranges from Industry 4.0 (production technology) with 40 %, to optical instrumentation with 38 %, defence and security with 22 %, components and materials with 19 % and to mobility with 17 %, to name only the most important examples.

The importance of photonics for Austria

In the field of photonics, Austrian research and industry largely mirror the European view as depicted in the Photonics 21 Roadmap. Austria's strengths lie, among others, in the sectors of lighting (general and automotive), integrated photonic circuits, sensor technology and production technologies. Market leaders as well as highly specialized small and medium-sized companies are an integral part of the international photonics landscape and provide valuable contributions to pioneering innovations.

Developments in the field of ***mobility and safety*** include matrix and laser headlights, state-of-the-art light detection and ranging or time-of-flight camera technologies for future autonomous driving and unmanned aerial vehicles, as well as fibre optic distributed acoustic sensing systems for real-time detection, tracking of trains and monitoring of traffic infrastructure.

In the field of ***life science, health and environment***, contributions for optical imaging techniques, in particular optical coherence tomography for non-contact, depth-resolved visualization of tissue are especially noteworthy. Achievements in sensors and methods for environmental monitoring, such as air and water pollution control or agricultural production, are also of major significance.

Intelligent, environmentally friendly ***lighting*** made in Austria is in use worldwide, whether with a focus on Human Centric Lighting aspects or for horticulture applications. Research into intelligent systems and efficient optical solutions has been on the agenda of companies and research institutes for years.

The same applies to Austrian ***sensor, production and quality assurance technology***. Austrian companies and institutes are currently working on photonics methods for non-destructive quality assurance developments. Lasers are the preferred energy sources not only for welding, but also for most types of 3D printing or additive manufacturing.

Modern ***information and communication systems*** would not be possible without laser technologies. Photons in fibre optic cables travel long distances with up to 20 times less loss, compared to electrons. Furthermore, photonic technologies are invaluable for data storage and for future novel computing units.

Austrian institutes and companies are also at the forefront of ***optical quantum technology*** worldwide, especially with the development of optical quantum computers. This can certainly be attributed to the high level of Austrian education and basic research in photonics compared to other countries.

Source:

[1] Steglich, P. & Heise, K., 2019. PHOTONICS einfach erklärt - Wie Licht die Industrie revolutionierte. Wiesbaden: Springer Spektrum. | [2] Bäuerle, D., 2009. Laser - Grundlagen und Anwendungen in PHOTONICS, Technik, Medizin und Kunst. Weinheim: WILEY-VCH. | [3] Photonics 21, 2019, Europe'e age of light, Düsseldorf: European Technology Platform Photonics 21 | [4] Tematys, 2020, photonics market data and industry report-2020



Figure 1: Intelligent process integration and date evaluation open up numerous new applications for miniaturized spectrometers.

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Sensors and Metrology

The high-tech-driven global photonics sensor market was valued at 13.25 billion USD in 2020 and is expected to grow at an annual growth rate of 17 % to 26.65 billion USD by 2026. The versatility of using sensor data for intelligent decision making (e.g. machine vision sensors) and the development of Industry 4.0 with connectivity, flexibility, artificial intelligence (AI) and speed in enterprise processes will further drive this market development. Regulatory requirements for safety and security are also a key driver of the photonics market, which continuously demands more compact, lighter, more efficient and more reliable devices and systems with higher performance and more functionality, which can be produced economically in large quantities.

Optics-based sensor technology can meet precisely these aforementioned requirements and in addition, has a large number of advantages that enable a wide range of applications. Two different basic target directions can be identified here: ***a) high-tech enhancements for consumer electronics and b) high-performance solutions for industrial sensor technology.*** There are highly relevant players in Austria and in Photonics Austria for both areas: These include a world-leading developer and manufacturer of photonic sensors and light sources for the realization of a wide variety of systems in the consumer and industrial markets and globally recognized research institutions for photonic systems for process-integrated industrial measurement technology.

Optical sensors enable non-contact high performance screening in industrial, healthcare and consumer applications. In recent years, ***miniaturization and cost reduction*** have taken place in this area, making it possible to use significantly more sensors than before. The combination of high precision optical sensors and high speed analogous to Complementary Metal Oxide Semiconductor (CMOS)-microcontrollers is required to develop future photonics-based sensing solutions that will revolutionize the functionality and performance of sensing systems. Software-based 3D sensing technology extends the ability of hardware to "perceive"

its real-world environment. Nowadays, smartphones, cars, drones and cobots widely use this technology. In smartphones, facial or gesture recognition is used in games or for secure banking and it has already changed the way we interact with them. In cars, 3D optical sensing will be key to autonomous driving, but interior applications such as gesture control, touchless dashboards or fatigue detection will also dramatically increase the safety and functionality of cars. On the internet, 3D augmented features based on sensor technology will change the user experience, for example in social media or e-commerce.



Figure 2: Lasers are an indispensable part of photonic sensor technology.

National Highlights

In the areas of sensor technology, lighting, as well as visualization, the Austrian company ams is on its way to becoming the market leader for components and solutions. However, in an international comparison, other Austrian companies and research institutions in this segment are also among the technological leaders. ***To remain competitive, companies' technology roadmaps must cover key photonics technologies*** (Fig. 3). This ranges from emitters, light modulators and detectors to technologies for integrated circuits, for data acquisition and manipulation.

Emitters

To pick just one type of emitter from the variety of emitters developed by ams, for example light-emitting diodes (LEDs), µLEDs, vertical cavity surface-emitting lasers (VCSELs)/edge-emitting lasers (EELs) and lamps, their VCSELs have the best power density in their class as well as the best conversion efficiency. These VCSELs cannot only be found in smartphones but also in solid-state light imaging, detection and ranging (LiDAR) applications for autonomous driving. There are several significant research topics in order to improve the efficiency: Particularly noteworthy are the optimization of internal quantum efficiency, the integration of diffractive optical structures for efficient light extraction and guidance and ultra-compact module integration.

Sensors

There are also ***international benchmarks from Austria*** in sensors, for example the TMD2636 sensor module, with which ams introduced the world's smallest proximity sensor for use in wireless earphones with a

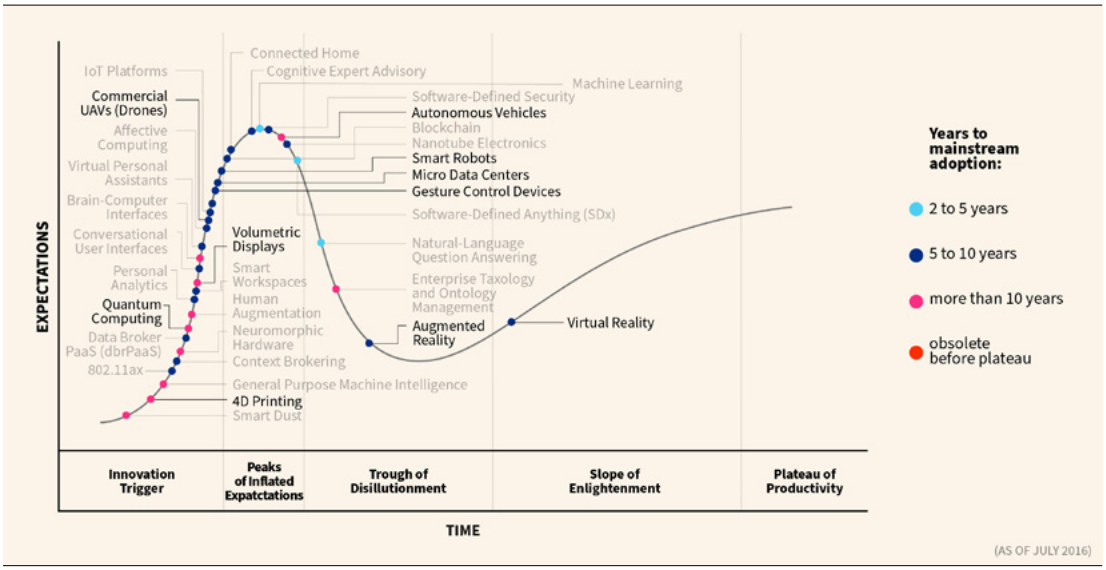


Figure 3: Gartner's Hype Cycle for emerging technologies shows the status of numerous photonic technologies, which are considered the basis for future applications.

housing volume of only 0.7 mm³ in 2021. This facilitates the integration of multiple sensors for reliable detection of usage. The earphone

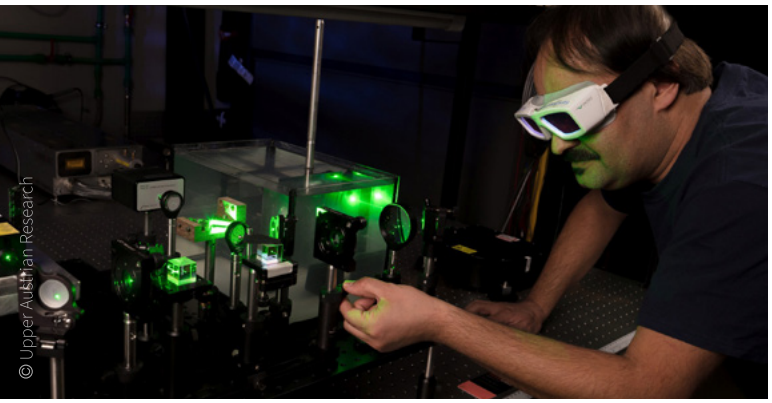


Figure 4: Adjustment of a laser

automatically turns on when inserted into the ear or turns off when removed. This increases the comfort for users and, most importantly, saves energy when the earphone is not in use.

Ultra-compact optical multichannel sensors in the visible to near-infrared range are used for spectral identification and analytical applications in mobile devices. The AS7341L multichannel sensor from ams provides spectrally resolved optical sensing. Based on this, the German Sanovia Healthcare was able to develop a COVID-19 lateral flow test within just nine months in 2020.

A good example of a very specialized Austrian company is XARION Laser Acoustics. The company develops and produces optical microphones with particularly high sensitivity and bandwidth, primarily for industrial applications in metrology.

Systems

Based on its early involvement with relevant future topics, the Upper Austrian research company RECENDT, has established a leading international role in photonic industrial sensor technology, such as laser-based ultrasonic testing, terahertz testing technology, optical coherence tomography (OCT) technology and microspectrometer technology. The latter in particular offers a tremendous opportunity for broad industrial application, as it opens up new potential uses through a leap in size, robustness and cost for the well-known infrared spectroscopy. The costs, for example, have already decreased from around 40,000 € to 400 € range– and further technological developments offer potential to reduce the cost to 4 €. This opens up interesting new application possibilities, especially for RECENDT with its broad expertise in process integration of sensor technology and related data evaluation. ***OCT technology***, which is discussed in detail in the chapter "Life Science, Health, Agriculture and Environment" (page 23), also ***offers considerable potential in industrial applications*** and will continue to benefit massively from joint research and development (R&D).

PICs (Photonic Integrated Circuits) represent systems of the smallest design. The chapter on Information and Communication Technologies (ICT) (page 27) outlines their importance in telecommunications. There has already been significant work done in the joint national project COHESION[1] by AIT and ams on "PIC for 3D retinal scans" or in the European project COLODOR[2] with a German partner "PIC for Volatile Optical Compounds (VOC)". For further industrial use, the creation of photonic design kits (PDKs) in particular will be an important prerequisite, as well as semiconductor process development for the integration of light sources, modulators, interferometers, optical filters and photodetectors made up of different material systems on one chip.

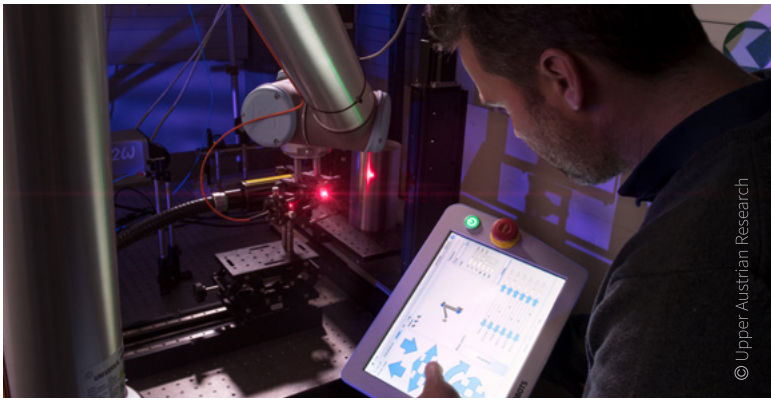


Figure 5: Photonic sensing is also perfect for robot-guided use.

In many cases, an important prerequisite for the widespread application of photonic sensors is the ***certification according to safety standards*** for industrial and public use. Particularly in the case of innovative technologies, this is often extremely complex and requires close cooperation between the innovation driver and the certification provider. The Austrian company tofmotion has taken this path and launched the world's first safety-certified ToF camera.

Research projects

PSSP – Photonic Sensing for Smarter Processes[3] is a national research project funded by the Austrian Research Funding Agency (FFG) and is part of the COMET

program. It deals intensively with questions of industrial optical measurement technology. As expressed in the project title, photonic sensing in industrial terms never just serves itself. It always has to have a purpose in the industrial manufacturing process; it has to optimize it, help increase the efficiency, avoid errors, guarantee safety, and build up a better understanding of the process to enable better models through digital twins. These topics offer further research potential for many years to come.

In Focus

The wide range of possible uses for optical sensors makes them equally interesting for consumer products and industrial applications. While many technologies and products can be assigned primarily to one of the two subject areas, rapid technical progress and cost reductions mean that in many cases they can also be used in both sectors.

High-tech enhancements for consumer electronics

The various forms of emitters play a significant role for consumer electronics. In addition to the optimization and further improvement of LEDs and VCSELs, the development and use of µLEDs is of great importance. They will serve as key elements for the next generation of displays, as they offer a longer lifetime than modern Organic Light Emitting Diodes (OLEDs) at higher brightness and are more efficient. The integration of sensors in µLED displays will also make mobile devices smarter.

Other key technologies in ***3D sensing*** include ***optical components and micromodules***. Mobile devices in particular are demanding ultra-compact lens modules, which is driving the development of multistack microlenses. In addition, diffractive optical elements such as flat lenses will find their way into applications to enable higher optical capabilities at a lower price. 3D sensing, for example structured light, already uses this technology. Further development of these key technologies will enable sensor applications ranging from ultra-small applications such as endoscopy to remote detection and acquisition (LiDAR).

Semiconductor-based detectors, either visible light or infrared, are other significant components. High sensitivity, low noise and high dynamic range are key technical properties of image sensors. High resolving power and high frame rates enable optimization of automated optical inspection to increase productivity in fac-



Figure 6: Outdoor capable ToF camera IC5 from tofmotion

GREEN PHOTONICS ASPECT

Photonics can also be used for fine-mesh monitoring of our environment, especially for assessing air quality. Instead of relying on regionally widespread weather stations for this purpose, users could use wearables equipped with a particle sensor to monitor their personal environment in real time and to react immediately to levels of particulate matter that pose a health risk. According to a study by the European Environment Agency (EEA), more than 400,000 people die prematurely each year in Europe alone as a result of particulate matter pollution. Furthermore, such sensors could also be easily and diversely integrated indoors and in public spaces – and can thus provide an unprecedented quantity and density of measured values or measuring points. Together with Graz University of Technology and Silicon Austria Labs, ams has developed an ultra-compact and energy-efficient sensor for mobile devices that informs users in real time about the level of particulate matter in the air and warns them in case of elevated levels. Such photonics-based sensors will raise public awareness of regionally varying environmental pollution and help to drive further regulatory action. These will be crucial in shaping our world to be greener, safer and healthier.

tories. They are also important for applications in security technology, intelligent traffic systems and video technology. In cell phones, new miniature ambient light sensors can be positioned in the gap between the screen and the phone's housing in edge-to-edge smartphone displays. The combination of multiple visible light and infrared light sensing photodiodes enables suppression of infrared interference and measurement of ambient light down to as little as 1 mlux, supporting display brightness management and improving camera image quality.

Fundamental key technologies for 3D sensing are based on photonics, for example ToF sensing, structured light and active stereo vision. ToF time-of-flight sensors (Fig. 6) illuminate the scene with ultra-short near-infrared light pulses and measure the time until the pulse returns to compute the 3D image. Structured light is based on projecting points (or other geometries) onto objects and measures the distorted patterns reflected back to represent 3D objects. In active stereo vision, two or more slightly offset cameras produce a stereoscopic image from which depth information is calculated.

High-performance solutions for industrial sensor technology

The main requirements for sensor technologies in industrial applications are technical performance, robustness, measurement speed, but usually also price, size and flexibility. Photonic solutions solve all these challenges – and if non-contact measurements are required, there is usually no way around photonic solutions. The areas of application are as diverse as the approaches to solutions and the available technologies. As enabler technologies for industry, the need for research in sensor technology is driven by industry requirements, but in the research funding landscape, it must also be considered as a key enabling technology (KET) in its own right.

In addition to simple systems such as photoelectric sensors or already very common laser probes/distance measuring devices, sensors of course include cameras. The ongoing development in this sector is impressive and driven by the consumer market. Resolution, speed, price and size are being optimized – but the range of applications is also expanding: imaging is no longer limited to the optically visible range. Chemical imaging (hyper-spectral imaging) provides information about the spatially resolved chemical composition of products or identifies impurities. For the characterization of chemical elements, for example in metals, spatial resolutions in the micrometre range can already be achieved using spark spectrometry or LIBS (Laser-Induced Breakdown Spectroscopy). In addition to chemical and imaging sensor technology in the near- and mid-infrared (NIR, MIR) the terahertz technology (THz) is also constantly developing. This allows the irradiation of thicker dielectric materials and the generation of structural 3D images or chemical information. For such applications, any form of X-ray-based measurement technology (radiography, XCT - X-ray Computed Tomography) is also available, which, while having higher safety requirements, provides almost unbeatable results for some applications. With microfocus X-ray equipment, even the smallest 3D structures can be resolved on a micrometre scale. For optically partially transparent materials, 3D structures in the micrometre range can also be imaged using the OCT method – without radiation protection requirements. This method is real-time capable and can be integrated in-line into processes. This aspect of process-integrated analysis (PAT - Process Analytical Technologies) has traditional-

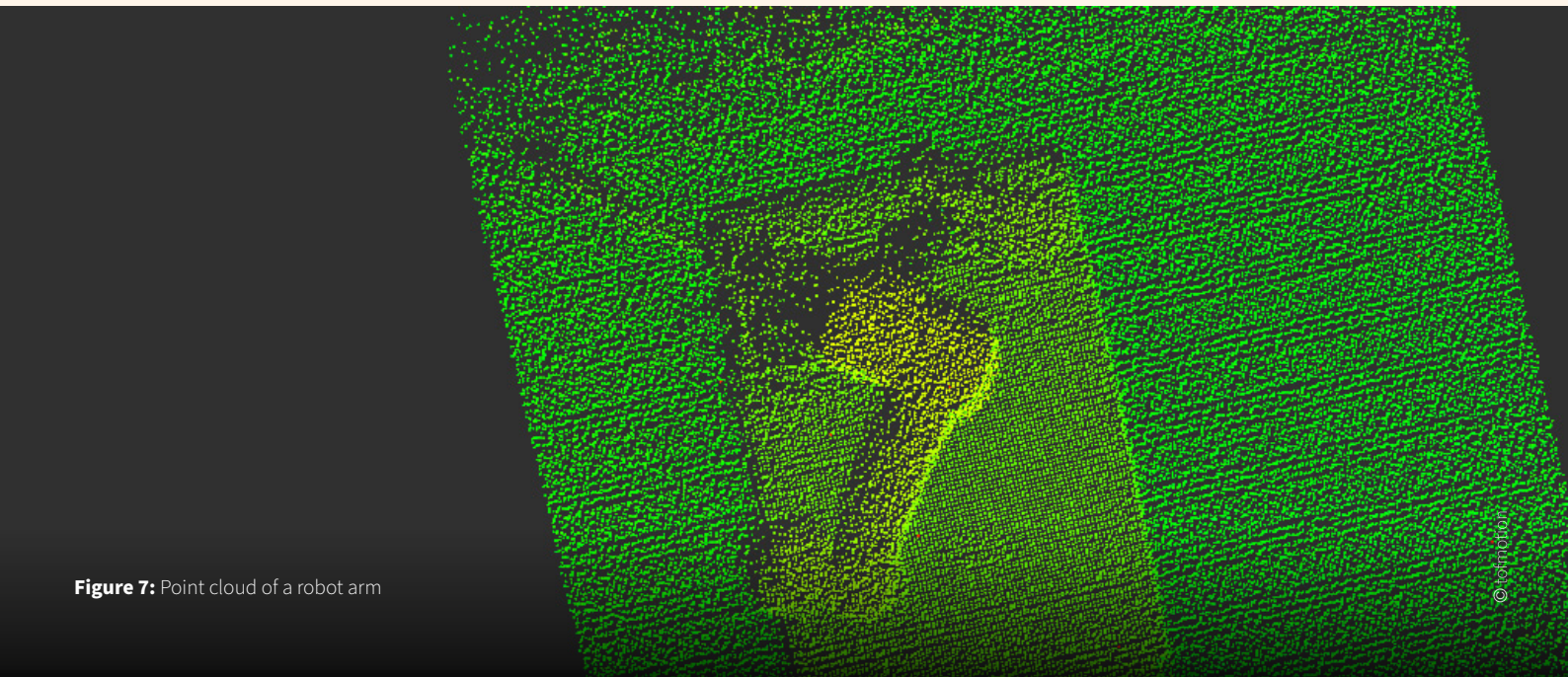


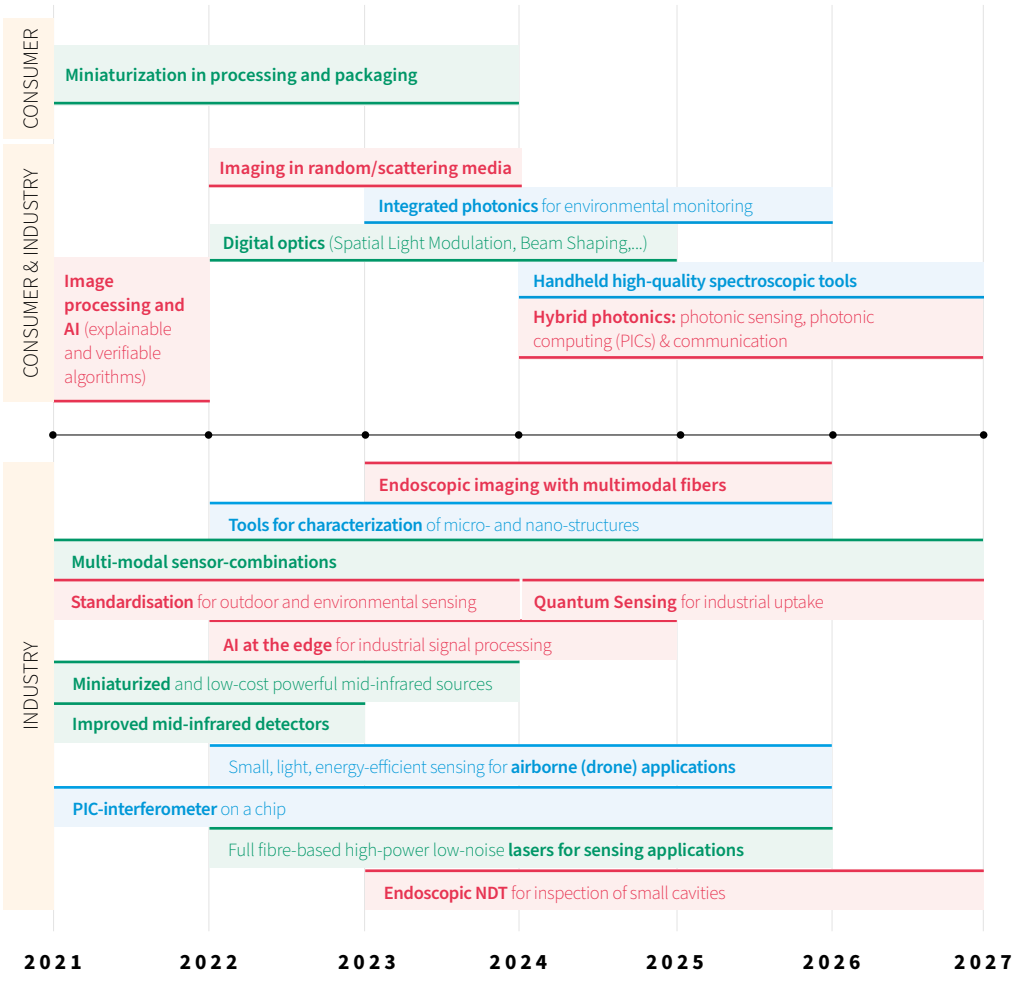
Figure 7: Point cloud of a robot arm

ly been very closely associated with the classical NIR (near-infrared) spectroscopic methods for chemical analysis directly in chemical and biochemical processes. For spectroscopic methods the current technological development is clearly moving towards small, flexible and cost-effective spectrometer modules – which in turn build the bridge to mobile consumer applications (for example, scanner applications for food, textiles, material recycling or drug testing).

The boundaries of photonic technologies are extendable: methods such as photoacoustic imaging or laser-induced ultrasound use photonic laser pulses to excite acoustic waves in the material. In thermography, light or even laser pulses are used to excite thermal waves. These methods enable the examination of materials that would not be sufficiently transparent or too scattering for purely photonic signals or waves. In any measurement technique, in addition to the physics of signal generation, the mathematics of signal analysis is a very important success factor. Many fundamental methods, such as super-resolution approaches can be applied equally to all wave types and can dramatically improve the results. ●

TIMELINE

● underlying technologies and applications ● challenges ● pioneering products



Source:

[1] COHESION: Meilenstein in der Sensor-Miniaturisierung zur Augendiagnostik, (ait.ac.at) | [2] COLODOR: Projekt mit Partnern aus Deutschland zum Thema PIC für VOC „volatile organic compounds" Detektion | [3] PSSP – Photonic Sensing for Smarter Processes, http://www.pssp.at/

Production and Quality Assurance

Production technology is undergoing a process of change, driven by the possibilities of new ICT and often referred to as the fourth industrial revolution. Additional innovation drivers are ecological and sustainability aspects, now subsumed at the political level under the term "Green Deal". Photonic technologies play a decisive role in this transformation. Two of the most formative developments of the last two decades, today's computer technology and the Internet, would not even be possible without them.

Modern manufacturing technology is also undergoing a photonic revolution, with earlier generations of industrial machinery increasingly giving way to ***lasers and sensors, usually in conjunction with robotic systems***. Photonic technologies are at the heart of the manufacturing sector's strategies for "Industry 4.0" – the development of a fully digitized and connected value chain from suppliers to customers that will enable a new era of high-precision, low-cost and resource-efficient production, as well as fast and flexible "mass customization" and new services around manufactured products.

This applies not only to photonic manufacturing processes, such as laser-based additive manufacturing, but also to quality assurance and to tracking. It is a core topic of Industry 4.0 and is increasingly dominated by non-contact and highly accurate photonic measurement technologies. In the production environment, they lead, among other things, to increased energy efficiency and the avoidance of rejects through zero-defect production. Related AI and Big Data (BD) applications for monitoring and optimizing manufacturing processes or entire production sequences are often based on the data of optical measurement technology.

National Highlights

European laser equipment manufacturers rank highly in the extremely competitive global market, even

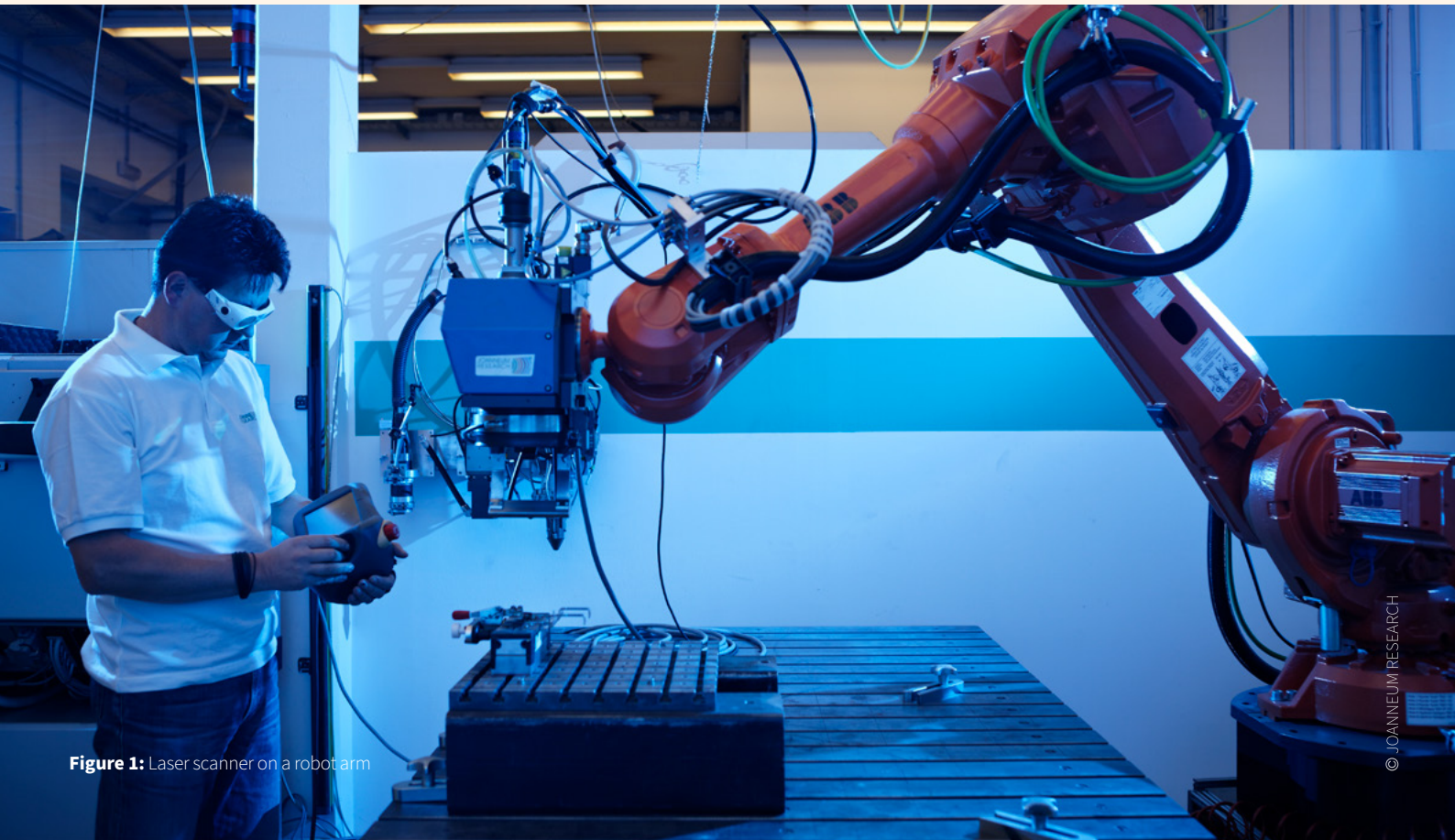


Figure 1: Laser scanner on a robot arm

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though many smaller manufacturers (including several Austrian laser manufacturers) have recently been purchased by large companies. Nevertheless, there are various players in Austria, especially in the field of laser-based manufacturing, which are very successful internationally with their respective activities:

Unique numerical simulations

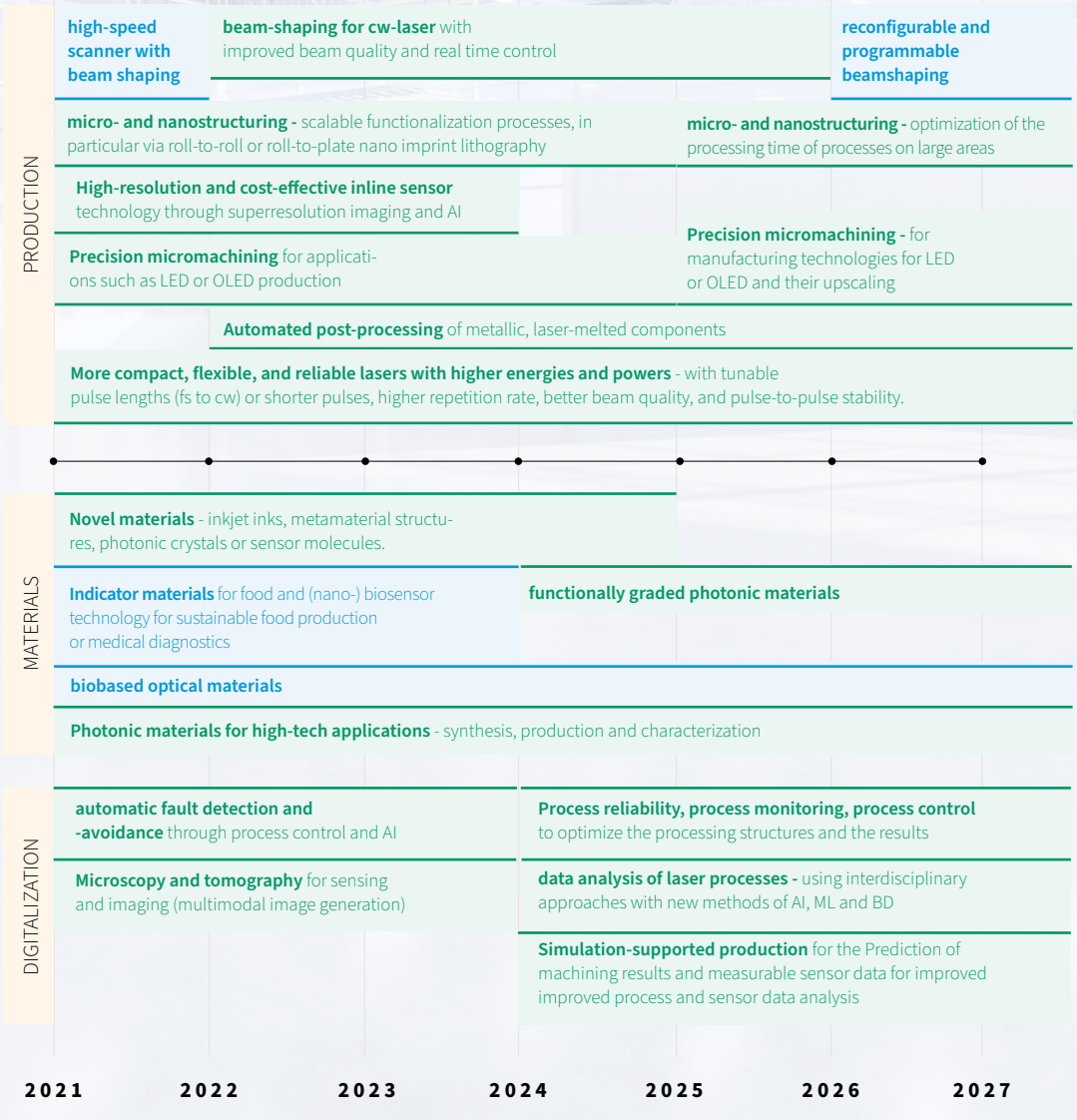
The Vienna University of Technology performs multi-physics, numerical simulations of laser material processing using an in-house developed software package for industrial companies worldwide. These ***unique simulations*** support the ***optimization of products and processes***, for example with regard to their environmental compatibility, and increase the resource efficiency directly.

In-line monitoring of laser-based manufacturing processes

Plasmo is a leading manufacturer of in-line monitoring for laser-based manufacturing processes, ISI Automotive is a manufacturer of airbags: Gas generators for airbags are safety components that require maximum control over the process steps. By means of op-

TIMELINE

• underlying technologies and applications • challenges • pioneering products



tical in-line inspection, a detailed analysis of critical weld seams is possible. ***This process eliminates the need for destructive testing of random samples***.

Functionalized surfaces

Functionalized surfaces (riblets, "sharkskin") developed by JOANNEUM RESEARCH and Bionic Surface Technologies using photonic methods of laser processing and UV microstructuring enable 1-5 % savings of kerosene in air travel, depending on their characteristics. They have proven themselves in the Red Bull Air Race and are being tested by a major European aviation company and further developed for civil aviation.

In Focus

Laser sources

In Austria, there are several players in the field of laser source manufacturing which have positioned themselves very successfully in niche areas. The activities relating to ultrashort laser pulses in Vorarlberg and Vienna are particularly noteworthy. In Burgenland, special CO_2 lasers are produced, especially for plastics processing. In the university sector, the Vienna and the Graz University of Technology, as well as the universities in Leoben, Graz, Vienna and Linz are successful in the field of fundamental research and applications for laser technology. Manufacturers of global significance are active in Austria as integrators of lasers in their devices and systems and globally active laser manufacturers operate local branches.

Lasers with shorter pulse durations enable novel processing methods and increased precision. Laser sources emitting ***pulses in the pico- and femtosecond range allow largely damage-free processing of a wide variety of materials***. Technological activities in the coming years will be dedicated to the development of more compact and reliable femtosecond lasers with higher energies and powers or shorter pulses, higher repetition rates, better beam quality and pulse-to-pulse stability for precision micromachining for applications such as LED or OLED production.

Laser production technologies

Applications of laser technology can be found in many sectors, both in large-scale industry and in small commercial enterprises. Various research institutions (e.g. JOANNEUM RESEARCH, Vienna University of Technology, and Vorarlberg University of Applied Sciences) are conducting research and development in the fields of laser welding, laser cladding, laser alloying and additive manufacturing (3D printing in powder beds and by laser cladding). Although laser technology already appears to be well established in production in many industries – such as the automotive industry, the metalworking industry and mechanical engineering – there is also great potential and need for research: the use of new laser sources as well as the further development and improvement of existing applications.

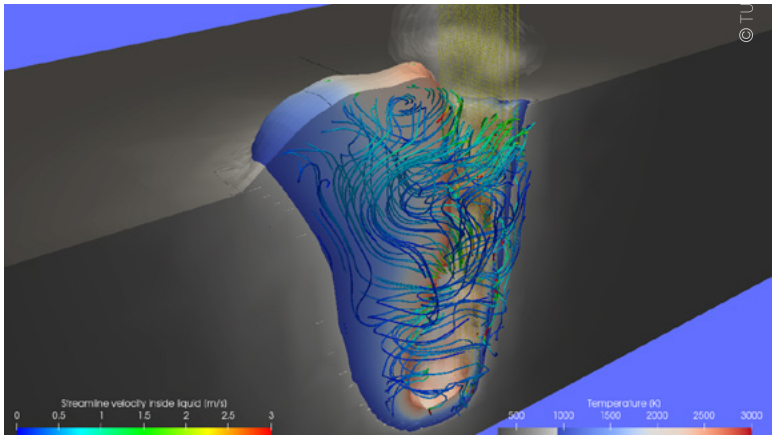


Figure 2: Simulation of a laser-melting-bath.
What cannot be seen is calculated.

Laser welding is an established joining technology in industry. Due to the development of new materials (e.g. high-strength steels, composites) and the increasing desire to join different materials (e.g. hard metal with steel or metal with ceramics) there are new research questions emerging in this field: automatic defect detection and prevention through process control, welding of complicated materials and material combinations, or beam shaping for challenging joining gap geometries. In the power generation and heavy machinery segment, laser cladding will be used for new custom optomechanical elements or on-site repair.

Nowadays, lasers with improved beam quality, high output power and excellent efficiency enable huge productivity gains in a wide range of applications. Beam shaping and combining lasers with other processing methods can open up new fields of application and the processing of new material combinations. ***Beam shaping, for example, will be used to influence or even tailor the microstructure of components*** by monitoring and controlling temperature fields in real time. This will also fuel the development of functionally graded materials and should make it possible to design multi-materials and produce them in the desired composition through additive processes.

Process analysis and monitoring

It is not only in the field of laser-based manufacturing

processes that a stronger link between inline process data acquisition, various sensor data (pages 9-14) and a deeper understanding of the process from process simulation can maintain and even expand competitiveness. ***Process monitoring and control, right through to process control for early fault detection and fault avoidance***, are therefore key issues for the future. ***Zero-defect production*** is an immensely important task, especially in today's world, given the need to make the best possible use of dwindling resources, avoid waste and ensure optimum recyclability. However, this still requires further efforts in sensor technology, monitoring/diagnosis, process understanding and simulation of machining processes.

3D printing of metallic materials in particular is an example of this: The technology brings enormous flexibility, time and material savings, as well as cost and energy savings in certain applications (e.g. lightweight construction/aerospace). This redefines the parameters of profitable manufacturing. Only the most comprehensive process understanding allows for the development of flexible and highest possible process stability with the upper most quality and minimal waste. This requires real-time measurements during the manufacturing processes.

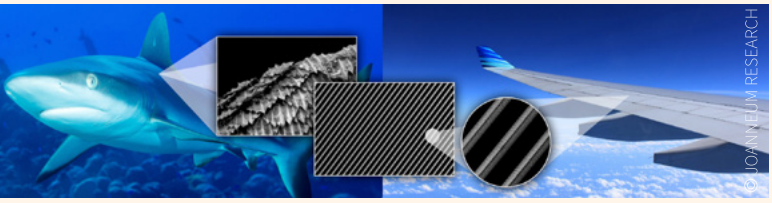


Figure 3: Laser-generated riblets help to reduce flow resistance and thus to save fuel.

For 3D printing, a holistic view of the process chain includes the generation of powders through to post-treatment for a product ready for sale. Solutions using photonic processes are available for the automated post-processing of metallic, laser-melted components (automated removal of support structures and surface smoothing).

In other macroscopic laser applications, improved measurement and quality control instruments, for example as tools for process monitoring during cutting or joining, can make a significant contribution to ensuring the correct process location. Significant Austrian players in this field include RECENDT (Research Centre for Non-Destructive Testing) and the companies Plasmo and XARION, which are driving R&D for photonic methods of in-line sensor technology forward.

The ongoing miniaturization of photonic components for quality control methods, such as spectroscopy, offers both technical and financial advantages. It is also spurring research into new materials. Research activities in microscopy and tomography for sensing and imaging enhance the spatially resolved 2D and 3D representation of specific material and system properties. In this context, the development of innovative multimodal image generation (e.g. a combination of visual camera-based inspection, X-ray CT, hyperspectral imaging at various size scales, thermography and terahertz CT) enables significant advances for multi-scale issues. This variety of ***non-destructive testing (NDT) methods must be implemented for industrial use as low-cost and/or high-speed technologies*** with interdisciplinary integration of current developments such as compressive sensing, super-resolution imaging, ML, edge and grid computing. For data analysis, interdisciplinary approaches with new methods of AI, ML and BD will be indispensable.

Process simulation for laser-based machining processes

Process reliability, defect detection and defect prevention pose major challenges for many companies in the laser technology sector. Laser machining processes can hardly be recorded in detail. Direct observation of the processes, for example during laser beam welding directly in the keyhole, is difficult and the determination of cause and effect almost impossible. Thus, in most cases, only secondary phenomena can be measured with sensors. The correlation of measurement data with defects during processing and consequently their active avoidance is of immense economic importance. ***Simulations are often the only way to gain a better understanding of the process*** and to obtain details about the machining process – specifically, defect formation and defect avoidance.

The further development of available simulation methods towards prediction tools, containing detailed sensor results and expected properties, requires further efforts. Thus, major challenges in the coming years include the development of simulation techniques for predicting measurable sensor data, the analysis of sensor data and their linkage with processing results and simulation results, as well as the linkage of these data with the materials, beam sources, processes and component properties in line with the objectives of "Industry 4.0".

Functionalization of surfaces

Precision material processing methods using ***ablation and surface structuring with short-pulse lasers (nano-, pico- and femtosecond lasers)*** are developed by JOANNEUM RESEARCH, the Vienna University of Technology and the Vorarlberg University of Applied Sciences for industrial production. In the corporate sector, for example, Rebeat Innovation is working on the fs-laser structuring of masters for the again booming vinyl record production. ***In the future, photonic functionalization of surfaces will lead to new, customized surfaces, structures and components.***

Selective micro- and nanostructuring can be used to locally modify desired component properties in a resource and environmentally friendly way, such as hydrophilic, hydrophobic or tribological properties. Previously mentioned developments of beam sources are intended to scale up the processes to large areas while at the same time optimizing the processing time and enabling the economical production of functionalized components. However, for the structuring of components, especially in the sub-µm range, the general understanding of the process is still very much in need of development. Questions of process reliability, process monitoring, process control and simulations for the selection of optimum machining structures and the prediction of results are also important topics for the coming years.

Photolithography, optical coatings and related technologies

In semiconductor technology, resolutions in the range of less than 10 nm are targeted for transistor structures, the modification and structuring of surfaces for which can also be carried out via lithographic processes.

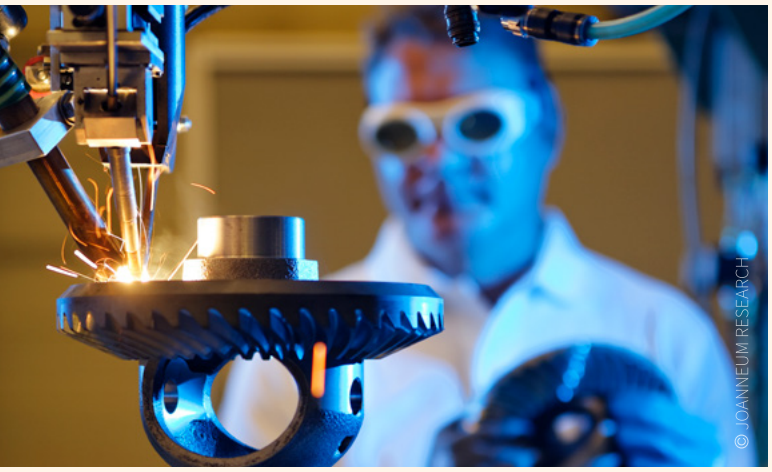


Figure 4: Laser welding of highly stressed gear parts for a safe ride.

Material and process development for photo- or electron-beam lithography or digital printing technologies will therefore play an increasingly important role. Thin optical and – more generally – photonic layers are a key factor for many applications. The focus of R&D in the coming years will be on novel functional optical or optoelectronic coatings, heterogeneous layer systems and the functionalization of surfaces to generate optically active components. Applications range from biosensors, colouring, light sources and detectors, to the building sector with energy efficiency improvements, to smart phones, solar cells and diagnostic devices. Emerging trends such as IoT (Internet of Things) and Industry 4.0 will also generate increasing demand for novel technological solutions. In the area of functionalization processes, micro- and nanostructuring, especially via roll-to-roll or roll-to-plate nano-imprint lithography, will find its way into industrial applications to complement classical semiconductor processes and enable new possibilities in micro-optics.

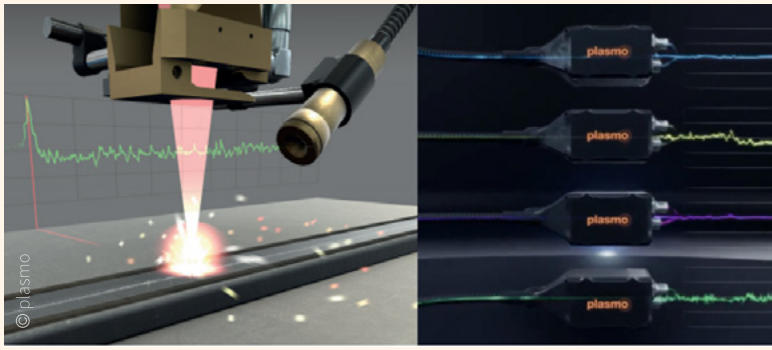


Figure 5: Optical analysis reveals production errors.

Life science markets and in vitro diagnostics will be addressed with microfluidic-based, lab-on-a-chip systems. These will provide essential contributions to appropriate technologies for the many millions of test strips needed, even after pandemic outbreaks such as the COVID-19 crisis, for a resilient society. Photonic processes are an essential foundation for nano-imprint lithographic mastering technologies.

However, these technologies are also interesting for PCB manufacturers or equipment manufacturers. Concerning materials, there are only a few companies dedicated to the chemistry of radiation-curing polymers (e.g. Allnex and Cubicure). Silicon Austria Labs, Vienna University of Technology, JOANNEUM RESEARCH and Profactor are active in this research field.

Photonic materials

Photonic materials play an important role for most of

the previously described key technologies. The area is very broad and includes sub-areas from established glass and semiconductor materials, polymer materials, tailored nano- and metamaterials, and emerging synthetic biophotonic materials, just to name a few. Austria has a solid scientific and industrial background in the production of glass and ceramic materials, glass fibers, low-cost polymer components and coatings, as well as in the development and production of tailored photonic materials, components or products.

Materials for photonics are also of great importance for the green deal while offering high future business potential. Central research priorities will be the synthesis, fabrication, and characterization of photonic materials for high-tech applications, the corresponding innovative manufacturing technologies and the upscaling of the corresponding processes. Micro- and nanometre-sized optical composites or glasses, glass-like optical materials and transparent (high-performance) ceramics (such as YAG ceramics), or novel alloys (glass-like, microalloyed) play a role as laser media, colour conversion materials (UV to NIR) or as components for low-loss optical signal transmission. Indicator materials for food and (nano-)biosensing for sustainable food production or medical diagnostics require innovations in inkjet inks, metamaterial structures, photonic crystals or sensor molecules.

Post scriptum

Better networking, both between research institutions and companies and between research institutions themselves, can provide a significant boost to innovation. This is of great importance, since research in the field of laser technology often requires very expensive infrastructure and interdisciplinarity. Intensive collaboration between physicists, laser engineers, metallurgists and materials scientists, but also AI and Big Data specialists is necessary to answer the increasingly complex questions in the development and application of photonic technologies. ●

GREEN PHOTONICS ASPEKT

According to the Photonics 21 Roadmap "Europe's age of light", the challenges of green manufacturing lie in realizing the technical and economic potential of sustainable production and highly efficient and emission-free production in urban environments. European factories should be fast, green and flexible by 2030. Photonic technologies inherently support a goal orientation towards efficiency increase, resource conservation and environmental sustainability, as well as the mission of a "true circular economy". Specifically, Photonics reduces CO_2 emissions, enables weight reduction and material savings, replaces chemical treatments and increases product lifecycle and sustainability. There are a large number of current examples: Novel gallium arsenide-based lasers have recently been developed and are the world's most efficient light sources. Without process-integrated monitoring by photonic sensors, the "zero-defect production" to avoid rejects would be inconceivable. Last but not least, many of the additive manufacturing methods are based on photonic technologies that enable revolutionary lightweight construction and efficient rapid prototyping.

Life Science, Health, Agriculture and Environment

Light is the basis of all complex life we know. Almost all forms of life depend directly or indirectly on the supply of energy through the biochemical process of photosynthesis. For humans and many animal species, visual perception is the dominant form of receiving information and interacting with the environment.

It is therefore not surprising that photonic technologies are paramount to the life sciences, which include aspects of health, the environment and agriculture. From a physical point of view, this importance is due to the interactions of light with the electron shell of atoms and molecules as well as with the mechanical rotational and vibrational states of molecules. Based on these ***light-matter interactions***, a rich and diverse toolbox of methods for analysing and influencing biological systems has been developed in the life sciences and is constantly being expanded and improved upon.



Figure 1: Light is essential for life and development.

In the health sector, ***improved photonic research tools, diagnostic methods and miniaturized measurement systems*** will make a significant contribution to the transformation of the healthcare system in the sense of so-called ***4P medicine*** in the coming years. The abbreviation 4P stands for predictive, preventive, personalized and participatory.

In environmental monitoring and agricultural technology, spectral, hyperspectral and multimodal imaging techniques in particular are playing increasingly important roles (e.g. in connection with precision agriculture). Furthermore, novel optical analysis techniques and portable sensor systems for testing air, water, and soil quality, as well as animal health will be of major significance.

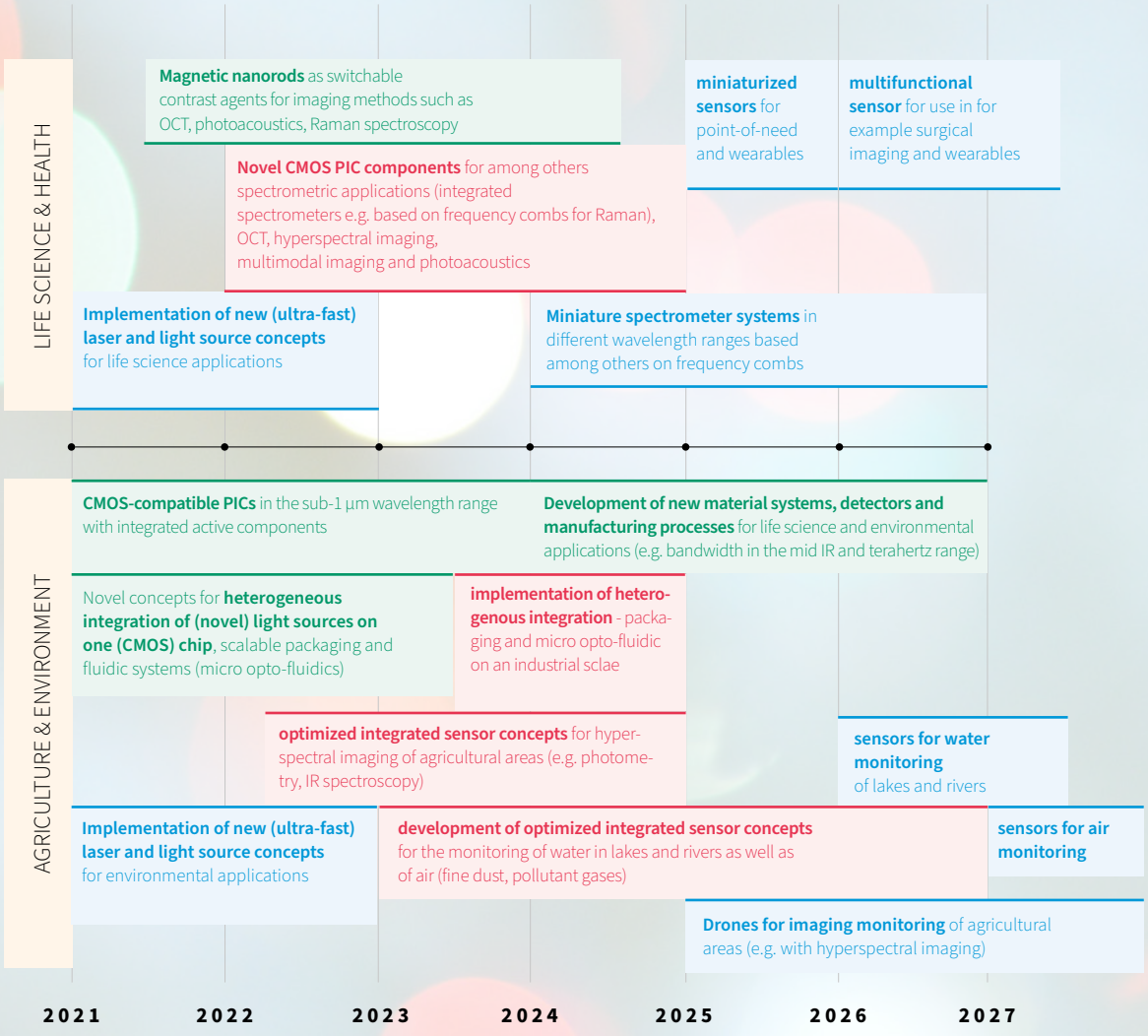
National Highlights

The technology of PICs based on integrated optical waveguides has come a long way in recent decades, driven by optical telecommunications. The successes in telecommunications have led to numerous efforts to use these PICs for life science applications as well. However, the concepts, materials, and manufacturing processes from the telecommunications sector only meet the requirements of biophotonic applications to a limited extent. For example, only a few wavelength ranges in the near-infrared are used for optical telecommunications, but a wide variety of spectral ranges are relevant in ***biophotonics***, ranging from the visible to the near-, mid-infrared and terahertz frequencies.

In addition, innovative concepts and photonic components, which do not exist for telecommunications applications, make many applications in biophotonics possible in the first place. Therefore, tailor-made solutions are needed for the various specific applications. This opens up new opportunities for the Austrian photonics R&D landscape, an extremely successful example of which are the activities of Austrian companies and research institutions in the field of integrated OCT . OCT is an optical imaging technique for ***non-contact, depth-resolved visualization of diverse materials and tissues.*** In medicine, OCT (page 11) has established itself as an indispensable diagnostic

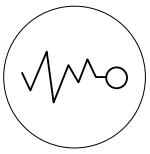
TIMELINE

• underlying technologies and applications • challenges • pioneering products



GREEN PHOTONICS ASPEKT

Clean drinking water is our most important natural resource. However, the quality is already massively impaired by the slightest contamination (e.g. microplastics, residues from various pharmaceuticals, pesticides ...). Problematic substances introduced into the water cycle usually spread quickly and unhindered throughout the entire ecosystem and promote biodiversity loss. Photonics enables continuous, automated water monitoring including necessary sampling and sensor systems for initial sample analysis. This is done by integrating optical analysis technologies such as photometry, Raman spectroscopy, or IR spectroscopy (FTIR) into the sampler and data storage or communication is performed using a built-in module. In this context, the link to an autonomous energy supply by means of flow generators and/or solar cells as well as the triggering of an alarm in the event of critical measurement results also reinforces the benefits of photonics.



method thanks to its unique capabilities, especially in ophthalmology (eye care). Previously, it was only possible to guess whether a disease was developing under the uppermost layer of the retina using a fundus camera and a great deal of experience. OCT provides images in real time, without significant stress to the examined person, and is comparable to an ultrasound examination. OCT devices are also comparable to medical ultrasound devices in terms of size, complexity and acquisition costs. So far, they have been primarily used in clinics, but also in some well-equipped medical practices.

Austrian partners have joined several project consortia to take an important step forward towards compact, low-cost and robust ophthalmic OCT devices with integrated optics.
The completed FFG project COHESION (2015-2019) plays a pioneering role in Austria. In this project, an exclusively Austrian consortium around the internationally operating semiconductor manufacturer ams was able to demonstrate the world's first "in-vivo" OCT images of a human retina with a chip-integrated spectrometer (Fig. 2). These results have been published in the renowned Nature journal "Light: Science and Applications". The spectrometer was conceptualized by the Vorarlberg University of Applied Sciences and the measurements were performed by the Centre for Medical Physics and Biomedical Engineering of the Medical University of Vienna (MUW).

The basis for this was laid in ams' long-standing collaboration with integrated optics experts from the AIT Competence Unit, Molecular Diagnostics. The manufacturing processes and basic photonic components of a silicon nitride-based waveguide platform were developed for a wide range of sensory applications. The integration of waveguide components and optoelectronic components, such as photodiodes and readout electronics, enables a very high level of functionality on a single chip. This means that corresponding sensor concepts benefit from the same advantages in terms of cost efficiency, performance and robustness that for example have also helped smartphones to achieve a breakthrough.

The next development step is being worked on in the EU Horizon 2020 projects OCTCHIP[2] and HandheldOCT[3], which should be more efficient by integrating optics. This innovative concept involves integrating multiple OCT units on a single chip. With a high degree of parallelism, the final diagnostic devices could surpass previous OCT systems in terms of performance. The goal of OCTCHIP is to enable a compact OCT device for the 850 nm wavelength range, based on the CMOS compatible waveguide platform from ams. In HandheldOCT, a portable OCT system for the wavelength range of 1060 nm is being developed using a special waveguide technology platform from imec. The latter should be so compact that it can fit in any doctor's bag.

In Focus

For the analysis of future-oriented photonic technologies in the fields of "life science, health, agriculture and environment“, it is helpful to keep the most important trend-setting framework conditions in mind. The growing proportion of older people in industrialized countries, caused by increasing life expectancy and low birth rates, poses major challenges for healthcare systems in many countries. The quality of healthcare must be maintained at a high level or even be further improved. Without healthcare costs exploding, people must be able to live as long, healthy and self-determined as possible. In economically weak regions of the world, a significant improvement in the medical care situation is needed to bring the quality of life of the population up to the level of industrialized countries.

At the same time, global population growth continues. The unabated high consumption of resources in industrialized countries, combined with rising living standards worldwide and the associated increase in global per-capita resource consumption are intensifying the destruction of ecosystems and eco-diversity on our planet. This is dramatically demonstrated by the ***Earth Overshoot Day***, the calculated day of the calendar year when human resource consumption exceeds the Earth's capacity to reproduce it in that year. Currently, the Earth Overshoot Day is in July. These developments are exacerbated by climate change.

A wide variety of technological tools is required in order to deal with these developments in the best possible way or to even counteract them. Photonic technologies contribute to finding solutions for these challenges.

Health

The previously mentioned factors are leading to a change in the health care system, away from pure disease management and repair medicine to health maintenance and prevention. In addition, there is a growing health awareness among the population. New technological solutions are needed in the following four fields

with photonics coming into play in a variety of ways:

Medical research (science) already possesses numerous indispensable optical instruments and photonic methods for gaining new insights that contribute to an improved understanding of diverse biological and biochemical processes and their connections with human health. Optical microscopy and other imaging techniques for visualizing relevant biological and biochemical processes, ex-vivo and in-vivo, play a major role in this context. In the upcoming years, researchers will be provided with more efficient tools for their studies through the further development of analytical methods, such as multimodal imaging by combining physically different measurement concepts (e.g. Raman spectroscopy, fluorescence, infrared spectroscopy, multiphoton microscopy) or improved methods for in-vivo studies (e.g. photoacoustic imaging using novel contrast agents). For example, acousto-optical detectors enable a massive increase in detectable frequencies by using optically readable polymer-based microresonators.

Avoidance (prevention) requires a high level of participation from individuals to keep well. For this purpose, devices that support people in disease-preventing measures in areas like "fitness", "lifestyle", "wellbeing" and "activity monitoring", "monitoring of health status" are used. So far, such technical aids for self-monitoring have primarily been used in the form of wearables for tracking biophysical parameters. In the future, optical measurement methods can also help to determine biochemical parameters (electrolytes, metabolites, inflammation markers, blood sugar) in body fluids such as blood, urine, saliva or interstitial fluid (tissue fluid). This requires compact and cost-effective photonic components that are able, for example, to perform spectroscopic analyses in the near and mid-infrared or fluorescence-based detection.

Prevention also includes hygiene. In this context, it is expected that, due to the increased awareness of problems caused by COVID-19, the demand for improved or novel components and equipment for UV-C disinfection will increase. In addition to viruses, mainly multi-resistant hospital germs need to be killed.

For ***detection (diagnosis)***, improved methods and equipment are being developed both for the earliest possible detection of diseases and for therapy support and monitoring after treatments. Decentralized diagnostics close to the patient are becoming increasingly important.

Optical methods have always been of great importance in ***medical diagnostics***. Molecular diagnostic methods are primarily based on fluorescence and chemiluminescence.

In recent years in ophthalmology, the non-invasive optical coherence tomography[1] (page 23) has led to a significant improvement in the early detection of retinal diseases. Furthermore, optical coherence tomography has been successfully introduced into dermatology and dentistry. Endoscopes enable a look inside the body. Microscopy of biopsy samples provides the basis for the decision-making for surgical interventions in cancer treatment.

A key factor in the development of technology is the ongoing trend toward ***decentralization of the healthcare system***. This results in a high demand for miniaturized measuring systems for near-patient diagnostics. Due to the internationally challenging situation during the COVID-19 pandemic, continuous growth in areas that contribute to the management of pandemics, with the improvement or new development of methods for molecular biological analysis and genetic sequencing procedures, for antibody detection, and for virus detection is expected.

Further advances in photonics-based technical aids and methods are also expected in ***treatment and healing (surgery & therapy)***. Light therapy methods are gaining increasing interest in this regard. Treatment and surgical methods can gain significantly in precision through the further development of laser light sources and miniaturized sensor systems for intraoperative monitoring and diagnostics. New substances for photodynamic therapy will also contribute to improved treatment success.

Environmental protection

Climate and environmental protection are among the greatest challenges facing mankind, and are mobilizing global efforts to decarbonize and achieve the goals of climate neutrality, preservation of biodiversity and natural habitats, reduction of the input of pollutants and waste into the environment, as well as the efficient use of raw materials and energy in a circular economy. Photonic technologies contribute to finding solutions for these challenges.

Especially for ***environmental monitoring***, primarily photonic measurement methods are used to test air, water or soil. Technological developments in this area are moving towards the detection and quantification

of substances with lower detection values and more compact and cost-effective measurement systems. These systems are needed to enable a denser measurement point network of stationary or mobile measurement units, which, through advancing IoT-networking, will allow for the development of AI-assisted early warning systems and other services for fine-mesh environmental monitoring. In air-monitoring, fine dust particles and pollutant gases are continuously measured and available via networked databases. The focus will be on monitoring heavily trafficked areas, urban intersections or landfills.

This is similar in the field of ***water quality and protection***. Rivers, lakes, groundwater and wastewater disposal and treatment are continuously monitored using a wide variety of measuring systems, whereby optical analysis methods such as photometry, Raman spectroscopy or infrared spectroscopy are employed. The development is moving towards the detection of even the slightest impurities like pesticides, microbiological contaminants, residues of various pharmaceuticals or microplastics.

Optical analysis methods are also used in the development of environmentally friendly vehicle technologies. For the ***operation of fuel cell vehicles***, hydrogen is stored in a tank, while the necessary oxygen is taken from the ambient air. Contamination of the ambient air by exhaust gases from conventional combustion engines can lead to poisoning of the cathode and thus to a significant reduction in the service life of the fuel cell system. The research project B.GASUS (fuel cell gas test system, duration from 2021 to 2023, funded by the FFG program "Mobility of the Future") under the project management of Virtual Vehicle Research, deals with the influence of environmental pollutants on fuel cell cathodes during real world driving conditions. It therefore makes an important contribution to increasing the efficiency of future mobility systems. Optical spectroscopic measurement methods are primarily used and the results are incorporated into the creation of simulation models for the prevention of damage to fuel cell systems.

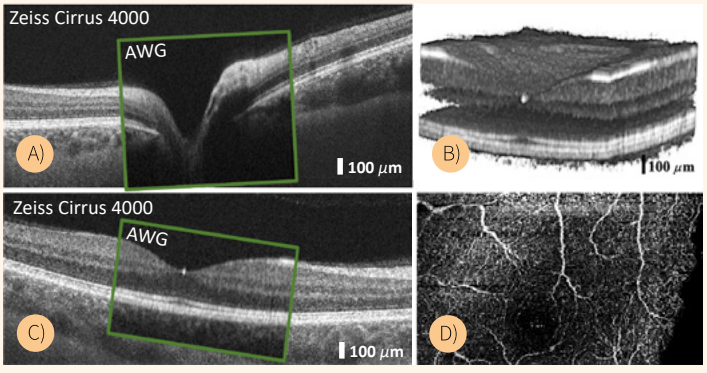


Figure 2: PIC based OCT images of a human retina | A) and C): Comparison of OCT tomograms (rectangular section) with those of a commercial device | B): 3D OCT tomogram of the optic pit | D): OCT angiography image of the micro vascular system

Agriculture and forestry

In the field of agriculture and forestry, extensive developments are taking place for monitoring fields and forests. This is possible due to technical advances in unmanned aerial vehicles (page 41) toward miniaturization and flight autonomy, which make systematic scanning of large areas possible and also due to improved, compact photonic measurement systems, for example for hyperspectral imaging coverage of agricultural areas with high spatial resolution. Forests play a central role in maintaining Earth's ecological balance, not least because of their capacity as carbon sinks. On the other hand, forest-, peat bog-, bush- and steppe-fires release more CO_2 into the atmosphere worldwide than the entire transportation sector. Systems and methods for detecting such fires are therefore important and today they are based almost exclusively on photonic technologies (Fig. 3). Satellite-based cameras in the visible and infrared wavelength ranges can help to efficiently monitor forest fires across the Earth's surface, assess damage and provide data for predictive models. However, these systems are of limited use for early detection because a satellite only flies over a region every two to five days. Automated systems on watchtowers or autonomous aircraft, such as CAMCOPTER from the Viennese company Schiebel, which use a combination of LiDAR, hyperspectral and high-definition cameras[5], are more efficient in this respect.

Hyperspectral imaging technologies are also increasingly applied in precision agriculture for increasing yields while avoiding over-fertilization and reducing pesticide and herbicide use. Smaller drones are now capable of bringing such systems to appropriate monitoring heights. Digital processing of hyperspectral data in real time is performed on increasingly powerful processors with software such as the latest development from the Graz-based company PerceptionPark.[6]

Nutrition

The "From Farm to Fork" concept stands for a healthier and more sustainable EU food system and is a cornerstone of the European Green Deal for environmental sustainability and for food and feed safety. In industrial food production, photonic sensors are ena-

bling ever-improving sorting techniques, not just for separating “good” from “bad”, but also for classifying into multiple grades. As an example, the potato sorters at Insort in Styria, equipped with hyperspectral near-infrared real-time cameras from the Graz-based company EVK, determine the concentration differences of starch and sugar to water in each scanned potato.

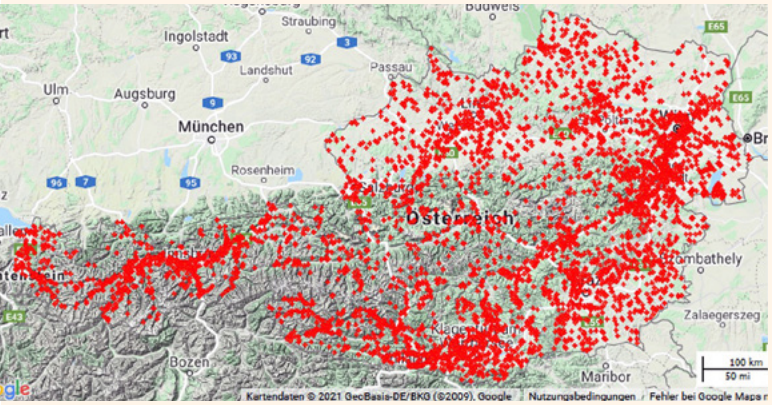


Figure 3: Wildfire detection systems and methods are now largely based on photonic technologies. [4]

This gives information for the further use of this food product. In addition to the research focus areas of life science, agriculture and food at the University of Natural Resources and Applied Life Sciences, the research center for "Feed and Food Quality, Safety and Innovation" (FFoQSI) has also been active since 2017. This COMET center bundles research expertise from various partners across a wide range of topics. Among others, photonic technologies, especially spectroscopy and hyperspectral imaging, have a high priority. These technologies have application potential, for example, in the observation and evaluation of green areas or farmland, for the assessment of agricultural products before or after harvest, for food safety relevant monitoring of cleaning or contamination in production areas as well as for quality control and process optimization in production.

Austria is also home to Anton Paar, a supplier demanded worldwide, of compact analysis systems, such as Raman spectrometers, Fourier Transform spectrometers, or refractometers. In addition to the long-established application in conventional laboratory analysis, spectroscopy is also increasingly penetrating into everyday production: For example in the form of portable handheld devices (trends: low-cost, miniaturization) or also on robotic vehicles and autonomously operating drones for fields or integrated into harvesting or processing machines. ●

Source:

[1] Elisabet A. Rank, Ryan Sentosa, Danielle J. Harper, Matthias Salas, Anna Gaugutz, Dana Seyringer, Stefan Nevlacsil, Alejandro Maese-Novo, Moritz Eggeling, Paul Muellner, Rainer Hainberger, Martin Sagmeister, Jochen Kraft, Rainer A. Leitgeb, and Wolfgang Drexler, “Toward optical coherence tomography on a chip: in vivo three-dimensional human retinal imaging using photonic integrated circuit-based arrayed waveguide gratings,” Light Sci Appl 10, 6 (2021): https://doi.org/10.1038/s41377-020-00450-0 | [2] Leitung: MUW; Partner: AIT, ams AG, Exalos GmbH, Fraunhofer IIS, Tyndall Institute, Carl Zeiss AG; 2016/01-2021/03 | [3] Leitung: MUW; Partner: imec, AIT, Innolum, Nanoscribe, Tyndall Institute, Carl Zeiss AG; 2020/01-2023/12 | [4] https://fire.boku.ac.at/firedb/de/ | [5] https://www.schiebel.net/wp-content/uploads/downloadBrochures/CAMCOPTER%20S-100%20Fact%20Sheet%20-%20Geophysical%20Survey/index.php) | [6] https://www.perception-park.com/

Information Systems and Communication Technologies

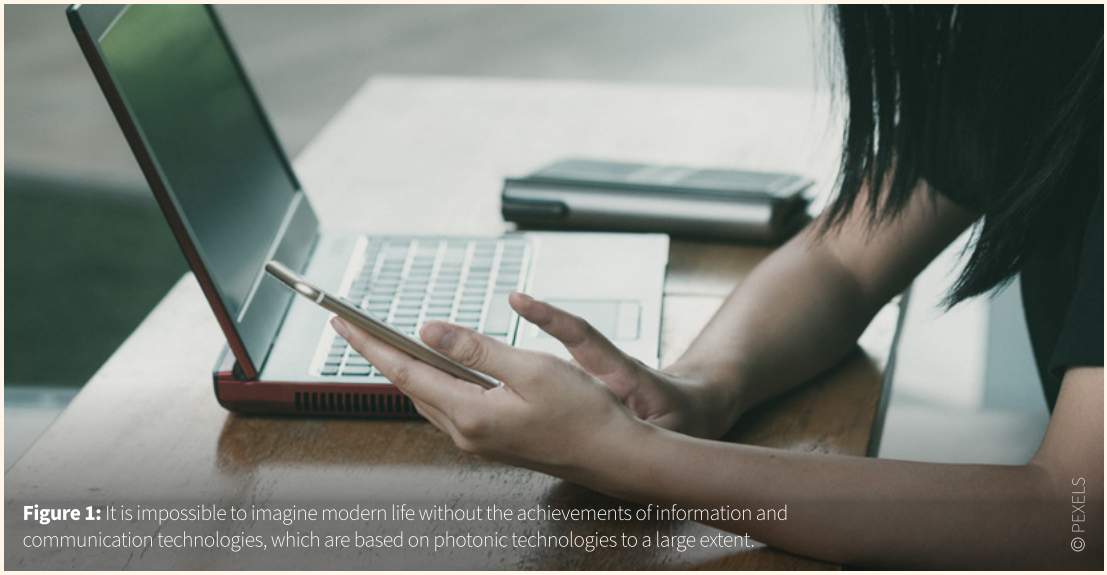


Figure 1: It is impossible to imagine modern life without the achievements of information and communication technologies, which are based on photonic technologies to a large extent.

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Since Graham Bell introduced the telephone, ICT has developed at breathtaking speed into a technology that permeates all areas of life. Today, advances in microelectronics make it possible to put up to 10 billion transistors on a microprocessor for computing power of up to 100 GFlops/s on the size of a fingernail. Although impressive, the capabilities of electronics are reaching their performance limits in terms of ***scalability of bandwidth while maintaining energy efficiency:*** computing power and data generation are currently growing at an annual rate of 60 %, which translates to approximately a hundredfold increase in data volume over the next 10 years.[1] This data tsunami will reach a volume of 175 zettabytes[2] in 2025 and will be accompanied by non-negligible energy consumption.

Photonics makes it possible to transmit information optically, setting several records at the same time: ***Optical telecommunications networks***, as the basis of the Internet, offer capacities of up to 10 Pb/s (=10,000,000 Mb/s) per optical fibre[3], which is as thin as a human hair. They connect entire continents over distances of more than 14,000 km,[4] and incidentally detect earthquakes.[5] Nowadays, 95 % of the transmitted information is transported via optical networks[6] that reach as far as the antenna masts of mobile phone networks. Another record will be achieved in terms of energy-efficiency (Green Photonics Aspect), which reduces the energy consumption of today's cloud infrastructure. In the underlying ***data centres,*** the successive migration from electronic data transmission between racks, circuit boards and – in the near future – between processor elements, to photonic systems has been taking place for several years.

Photonic ICT can also be found in many other applications, such as transportation infrastructure, industrial manufacturing plants, high-performance computing and even in the end-user sector. The provision of a modern ICT infrastructure is essential for several IT applications with high bandwidth requirements, low latency and cloud-based, i.e. centralized data processing.

National Highlights

Monolithically integrated silicon optoelectronics

Photonics is capable of transmitting information at high bandwidths with low power requirements. Electronics, on the other hand, enables the processing of informa-

tion. Therefore, a highly efficient interaction of transmission and transformation of information requires a highly efficient interface between photonics and electronics. In addition, established manufacturing processes should satisfy their seamless transition. A representative example from the field of monolithically integrated silicon optoelectronics is provided by an initiative from ams, the AIT Austrian Institute of Technology, the Vienna University of Technology and Intel Austria:

By using silicon-based semiconductor manufacturing, high-frequency microelectronics for up to 10 GHz of bandwidth as well as optoelectronic signal converters and passive optical functions were realised as PICs on wafer level. Both worlds were merged into a single wafer through three-dimensional stacking to enable aggregated data rates of up to 80 Gbit/s per data transmission channel on a small chip area with high energy-efficiency.

Data matrix on ceramics

Photonics is making another important contribution to dormant information. The Austrian start-up Ceramic Data Solutions is currently working together with the Vienna University of Technology, the University of Vienna, RE-

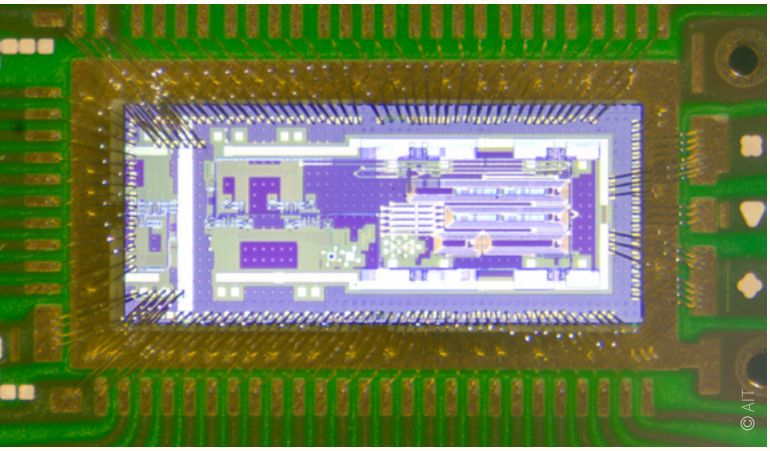


Figure 2: Silicon optoelectronics unified into a single wafer by three-dimensional stacking enables high efficiency in the smallest possible space.

CENDT in Linz and the AIT Austrian Institute of Technology on the fundamentals of a novel optical data storage technology based on ceramic coatings on sapphire glass wafers. The very hard, temperature-resistant coatings and substrates are selectively ablated in the nanometre range using femtosecond lasers and thus data is stored for extremely long time-periods. Multilayer coating systems can be expected to achieve storage densities of up to 1 TB per 100 cm2. Writing speeds of up to 1 GB/s are achieved using ultra-fast digital micromirror devices. Estimated energy consumption per bit written or read is expected to be less than 1 nJ. Energy consumption for long-term storage is negligible because the ceramic storage media do not require any air conditioning

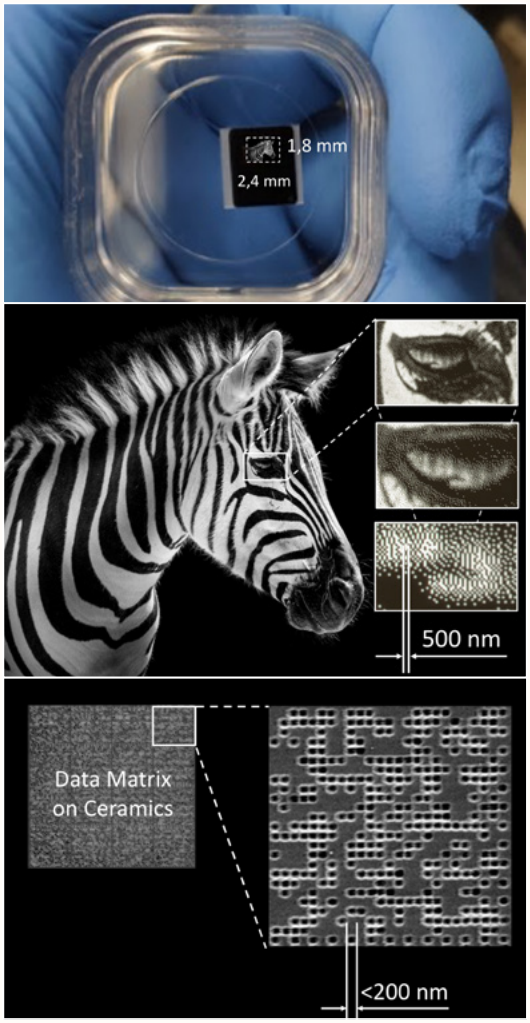


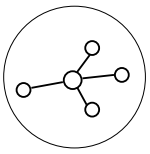
Figure 3: A novel optical data storage technology based on ceramic coatings on sapphire glass wafers helps reduce energy consumption for long-term storage.

In Focus

Research activities in photonic ICT in the coming years will address the development of components and systems for heterogeneous optical networks (industrial, telecom, data centre, home, space), new approaches for processing massive data streams (hardware for AI, high-performance computing) and robust data storage. These challenges are supported by continuous and systematic technology development in the field of PICs.

Data Communication: Performance with simultaneous energy-efficiency – between processor cores or across continents

The digital transformation of the 21st century is accompanied by a flood of data, which can only be handled with correspondingly powerful physical communication channels. Already today, almost all bits are trans-



mitted optically. However, optical communication channels are not limited to traditional internet connections, which are often already supported by fibre-optic networks right into the home. They span, in terms of transmission distance, over ten orders of magnitude from on-chip communications between processor and memory cores in supercomputers and optical waveguides on printed circuit boards and backplanes in data centres, to indoor light-based radio technology, fibre-to-the-X, and the interconnection of antenna systems of mobile networks, to urban, rural, transnational and intercontinental communications networks. Digitization driven by optical communication not only creates jobs, but also increases a country's innovative capability: If the level of digitization increases by 10 %, the unemployment rate is reduced by 0.84 % on average and the ranking in the global innovation index increases by 6 %.[7]

In telecommunication networks, the provision of bandwidth plays a crucial role in establishing new applications. COVID-19 in particular has highlighted the need for a corresponding bandwidth supply: An approximately 40 % increase in bandwidth-requirement to cope with daily professional and private activities[8] corresponds to an acceleration in the increase in demand of approximately 3-4 years.[9] Often inconspicuous, optical networks form the backbone of modern ***access and mobile networks***, which support new services such as virtual reality and transmit received radio signals as digital signals to a data centre via optical transport. In return, signals – received through targeted optical feeds – are transmitted by antenna stations. In particular, the larger signal bandwidths planned from 5G onward highlight the importance of such an optical "fronthaul," which in the future will merge with optical line-based technologies from the access sector. A disruptive approach to passive optical access networks is expected for this next generation of access (NGOA), for example by establishing coherent rather than direct signal detection, as has been in use in classical radio networks for many decades. For 6G, frequencies of more than 100 GHz – up to the terahertz range – are expected, which also entails a technological leap with regard to optoelectronic components (e.g. receivers, beamformers) but also new concepts. The integration of transportation infrastructure resources (e.g. lighting) will play an important role. Optical technology will not be limited to wired communication, but will also integrate concepts of broadband optical radio (Light Fidelity (LiFi)). LiFi also offers the possibility of providing high data rates in the 10 GHz range for mobile end devices in the office and consumer area, while at the same time providing interference-free and spatially limited communication. This allows, compared to the rather narrowband Wi-Fi, a transfer of large data sets with minimum duration and latency and thus connection to private or public cloud services.

In industrial facilities, the ***"Industrial Internet"*** is a major driver of innovative solutions through manufacturing automation, collaborative robot swarms and teleoperation based on real-time video-based remote control. Communication technology that is robust to electro-magnetic interference and has high data throughput (Tb/s) with deterministic latency (ms) plays a central role.

Information factories, on the other hand, require the integration of optical communications technology at smaller scales. The traffic in ***data centres*** is particularly critical, as each bit on long-haul networks results in approximately 100 bits of traffic in these neuralgic points of modern cloud infrastructure. Thus, the largest amount of data (approx. 75 %) is also clustered in these information factories. At the beginning of 2020, there were already 510 of these "hyperscale" data centres,[10] housing more than 5000 servers. Optical communication between server racks, printed circuit boards, processors and their cores, is crucial to drastically reduce the energy requirements of the information exchange between the individual data processing units. In this area, efficient optoelectronic transceivers and their integration in connection with waveguides, integrated in printed circuit boards, are in particular demand.

Optical communication is not limited to terrestrial networks and data centres. ***Photonics in the sky*** is playing an increasingly important role: Seamless coverage or ensuring connectivity with new services requires a partial shift of ICT infrastructure to the sky. High-altitude platforms and drone-based systems will ensure not only broadband access but also quantum communication for rural and urban areas. This "photonic air" will also be supported by satellites, with first demonstrators of an orbital satellite network and earth-to-satellite links with Tb/s capacities already in preparation.[11] Photonics also contributes to radio technologies by replacing broadband analogue radio modules in satellites, which are difficult to implement, with photonic functions. Technological challenges include the simplification of optical antenna systems, which require much more precise alignment than radio frequency technology, and the realization of optical beamforming – similar to that used in traditional radar systems

and in 5G millimetre-wave radio technologies. Optical ICT is also spurring the field of sensor and ***quantum technologies on*** through technological synergies. The merging of sensor and communication technology can be found, for example, in connection with LiDAR in networked mobility. The integration of energy harvesting can also enable new, energy-autonomous applications. Optical telecommunication methods also form the basis of numerous systems in the field of quantum communication.

Data Processing: The convergence of optics and information technology

A major challenge with high exploitation potential exists in the area of optical computing and ***optical neural networks***. While there is currently a migration of communication interfaces away from electrical and towards optical technologies, the processing of the data itself takes place on a purely electronic level. This leads to a bottleneck in processing due to the low throughput of the von-Neumann architecture, as well as excessive energy consumption. For example, an arithmetic operation today for multiplying and adding requires an energy input of 100 picojoules. In contrast, the human brain – a masterpiece of data processing and a processor that is not only different on a physical level but also has a different architecture – masters this in the sub-attojoule range. Thus, it is more efficient by ten to the power of eight. The desire for bio-inspired, neuronal circuits in which the brain's natural processing procedures are reproduced is therefore more than justified. Photonics offers a scalable solution: The human brain is built on approximately 1011 neurons, each with about 104 synapses. This large number of connections between the nodes of the network is difficult or impossible to address electronically, whereas photonics can use additional multiplexing dimensions such as optical frequency. In addition, it offers a higher information density for the temporal coding of the neuronal action potentials. This enables time-critical applications such as low-latency pattern recognition. Optical neural networks should be designed to be reconfigurable and programmable for this purpose, so that they can learn and adapt optimally to the application parameters. In the future, optical neural networks will contribute powerful and energy-efficient ***hardware for AI*** and ***co-processors for high-performance computing.***

Data Storage: High density and longevity

Another requirement of ICT is the storage of data for short but also long periods of time. The efficiency of data storage in terms of resource consumption and energy requirements depends very much on the storage media selected. Currently, data centres use media with short life cycles, typically 3-5 years, such as solid-state drives for fast-moving data streams, hard disk drives (HDD), or tape drives for longer-term storage. These types of drives are fragile, have high power requirements, and require permanent migration of stored data – though this migration cannot be performed in a resource-efficient manner. Photonic storage technologies such as ceramic data storage offer an attractive alternative for large data archives. They combine the know-how of optical storage media (Digital Versatile Disc (DVD)) in terms of optical write and read devices for data pixels in the nanometre range and thus achieve a high storage density of up to 1 TB per 100 cm2. By using ceramic substrates or thin ceramic layers, data can be stored over an extremely long period of time (100,000 years) with the lowest possible energy consumption and cost. With write rates in the Gb/s range and an energy consumption of approximately 1 nJ/bit, this corresponds to an energy reduction of 99 % compared to hard disk drives (HDDs). In addition, such data storage devices are robust against temperature fluctuations (up to 1200°C) and external influences such as chemicals or radiation.

Photonic Integrated Circuits: originated from ICT, paving the way for ICT

The impressive achievements of ICT in recent decades owe much to the rapid progress of electronic circuit integration and the associated scalability combined with reproducibility and robustness. Similarly, the breakthroughs in most of the aforementioned ICT areas will

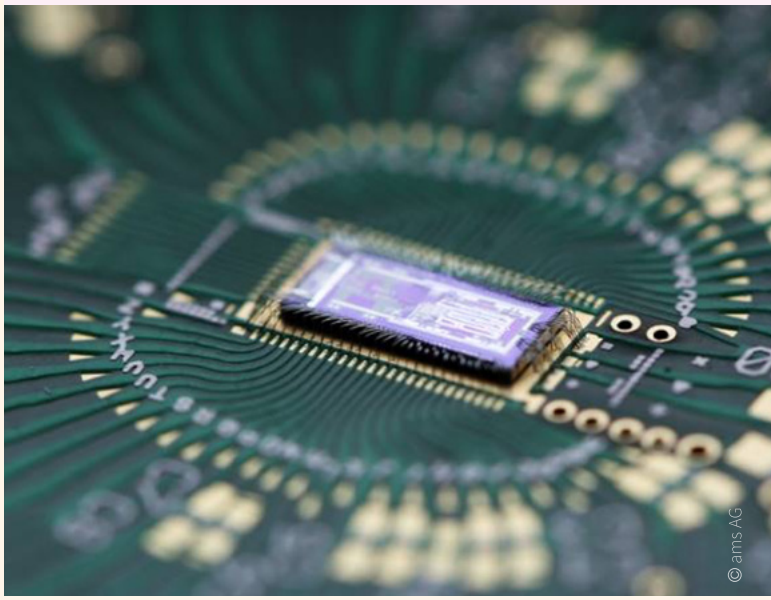
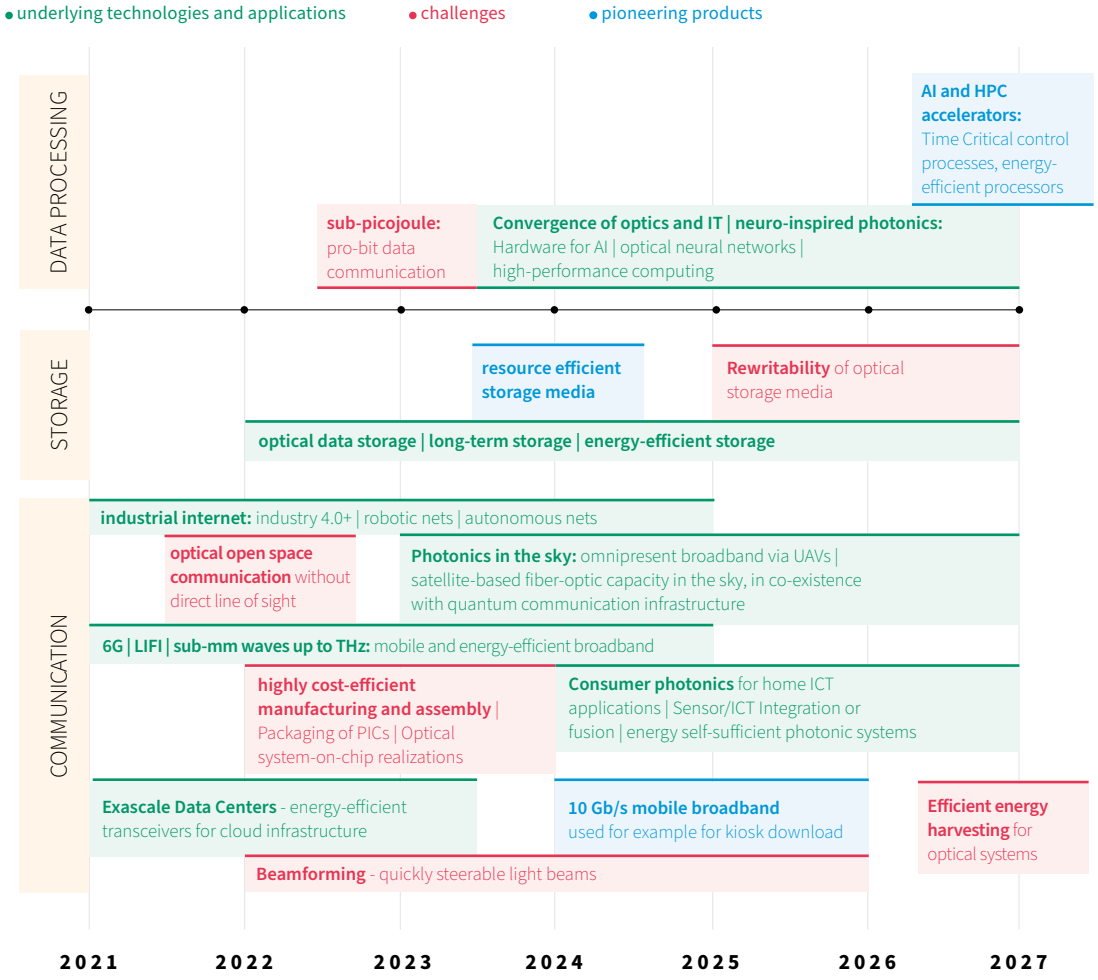


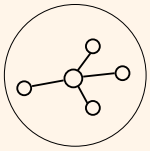
Figure 4: Integration of a wafer-level photonic circuit of an optoelectronic signal converter with silicon-based microelectronics.

TIMELINE



GREEN PHOTONICS ASPEKT

Global data traffic today already estimates an energy requirement equivalent to 24 nuclear reactors or 3-4 % of the global CO_2 emissions – a value comparable to that of commercial aviation. The rapidly growing share of ICT in global energy consumption could already be as high as 21 % (or 9000 TWh/year)[13] by 2030. Photonics can significantly counteract this trend in the three core areas of ICT: Optical data transmission, with an energy consumption of 2 pJ/bit, is many times more efficient than electrical methods, which require more than 1000 pJ/bit. Data processing can achieve a 20-fold increase in computing power through hybrid optoelectronic systems for the same energy consumption in the area of high-performance computing and AI hardware. All-optical implementations would provide a further order of magnitude increase, enabling up to 1 trillion computational operations per watt every second.[14] Data storage in modern mass storage devices such as solid state drives (SSDs) and HDDs consume between 30-60 nJ/bit per year when operating in data centres and cloud services. Data storage must be replaced and data migrated every 2-3 years. When using optical storage systems, the energy demand and resource consumption is reduced by a factor of 100.



be accompanied or only made possible by leaps in innovation in the field of photonic integration technology. The realization of circuits with corresponding functional density and reproducibility is the backbone of all current records in the field of photonic ICT.

The ***monolithic realization of high-frequency and optical functions through 3D integration***, which are supplemented by optical sources in a hybrid approach, is for example a central topic in broadband applications. Heterogeneous integration of tailored solutions in a system-on-chip, for example based on 2.5D integration, will also be of great importance for 6G applications. In connection with new material systems, which are not compatible with conventional silicon oriented manufacturing, hybrid integration is essential.

Experience from microelectronics shows that the mass market can only be addressed through on-chip integration and the associated drop in costs. Compared to microelectromechanical systems (MEMS), photonic integrated circuits (PICs) are characterized by higher stability against environmental influences such as vibrations, humidity or temperature fluctuations and can be produced with fewer rejects. PICs emerge from the field of optical telecommunications. ICT has always been the dominant application, with a 39 % share of the PIC market.[12] While electrons in microelectronics can be steered around corners by arbitrarily routed conductors, this is not so easy with photons. Therefore, the integration of beam splitters is one of the challenges in PICs. Compared to the Y-junctions used so far, so-called multimode interference (MMI) couplers allow much more compact solutions that are easier to integrate. At the same time, they are easier to produce because there are no branch points between waveguides. The next integration stage is the use of photonic crystals (PC). Similar to a semiconductor crystal, PCs have a bandgap that prevents light from staying in certain areas. This allows light to be guided at right angles even in the most confined spaces.

Similar to what has been achieved in microelectronics through field-programmable gate arrays (FPGAs), it is also essential at the photonic technology level to replace "rigid" functions with ***flexible functional elements to enable (re)configurable circuits as well as the provision of fully programmable photonic resources.*** Although the integration density with up to 1000 elements per PIC is currently still lagging behind that of microelectronics, a steady performance increase similar to Moore's law,[15] which states a doubling of processor performance every 2 years, is emerging. ●

Source:

[1] P. Winzer et al., "From Scaling Disparities to Integrated Parallelism: A Decathlon for a Decade," J. Lightwave Technol., vol. 5, pp. 1099-1115 (2017). | [2] D. Reinsel et al., "Data Age 2025 – The Digitization of the World," IDC-Seagate white paper, 2018. | [3] D. Soma et al., "10.16 Peta-bit/s Dense SDM/WDM transmission over Low-DMD 6-Mode 19-Core Fibre across C+L Band," in Proc. Europ. Conf. Opt. Comm., Gothenburg, Sweden, Sep. 2017, Th.PDP.A1. | [4] A. Turukin et al., "105.1 Tb/s Power-Efficient Transmission over 14,350 km using a 12-Core Fiber," in Proc. Opt. Fiber Comm. Conf., Anaheim, United States, Mar. 2016, Th4C.1. | [5] M. Cantono et al., "Sub-Hertz Spectral Analysis of Polarization of Light in a Transcontinental Submarine Cable," in Proc. Europ. Conf. Opt. Comm., Brussels, Belgium, Dec. 2020, Th2H.2. | [6] UNEP, ICPC, "Submarine cables and the oceans: connecting the world," Report (2009) | [7] K. Sabbagh et al., "Maximizing the impact of digitization," PwC report, 2012. | [8] OECD, "Keeping the Internet up and running in times of crisis," OECD Policy Responses to Coronavirus (COVID-19), May 2020. | [9] E. Harstead, "10G PONs are here and solve FTTH. What's really next for PON?," in Proc. Europ. Conf. Opt. Comm. (ECOC), Brussels, Belgium, Sep. 2020, Tu6A.1. | [10] Synergy Research Group, "Hyperscale Operator Spending on Data Centers up 11% in 2019 Despite only Modest Capex Growth", Mar. 2020 | [11] H. Hauschildt et al., "HydRON: High thRoughput Optical Network," Proc. SPIE, vol. 11272, p. 112720B, Mar. 2020. | [12] JePPIX Roadmap 2018: The Road to a Multi-Billion Euro Market in Integrated Photonics," Joint European Platform for Photonic Integrated Components and Circuits, 2018. | [13] N. Jones, "The Information Factories," Nature, vol. 561, pp. 163-166, 2018. | [14] Y. Shen et al., "Deep learning with coherent nanophotonic circuits," Nature Photonics, vol. 11, pp. 441-446, 2017 | [15] M. Smit et al., „Past, present, and future of InP-based photonic integration," APL Photonics, vol. 4, p. 050901, 2019.

Intelligent Lighting for urban and rural Applications

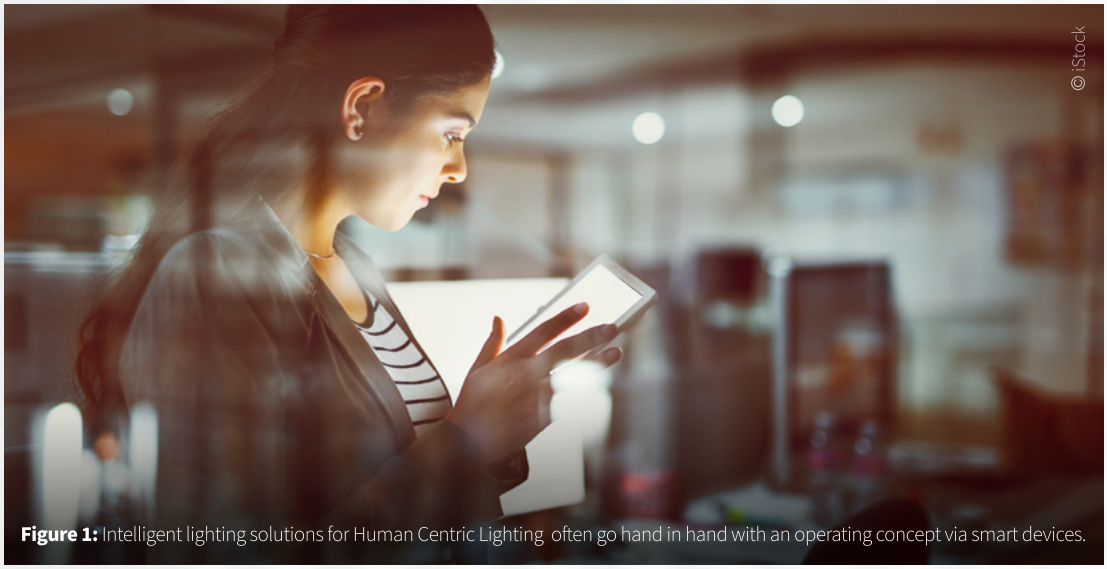


Figure 1: Intelligent lighting solutions for Human Centric Lighting often go hand in hand with an operating concept via smart devices.

Whereas lighting systems used to serve only to illuminate a room or area, nowadays more and more additional functionalities and benefits are expected from them: ***light is not only for seeing*** (visual), but also has a major impact on our mood, well-being and health (non-visual). The consideration of this fact in lighting systems was first expressed by the term ***"Human Centric Lighting"*** (HCL) by the consulting firm A. T. Kearny in 2013 as part of a market study commissioned by the European industry association Lighting Europe and ZVEI. To date there is still no clear definition. However, it is clear that light acutely increases alertness, enhances work, memory and attention performance and can alter specific physiological parameters. Plenty of light during the day supports the circadian rhythm (sleep-wake cycle). Too much light at night suppresses the release of the hormone melatonin and disrupts this rhythm, which in the longer term affects sleep quality and health (e.g. significantly increased cancer or type II diabetes risk).

Lighting should consequently consider non-visual effects and thus have a positive impact on human health. Lighting systems should be able to affect the mood of the user and the situation. For example, an adapted spectrum – through LED lighting with variable light colour and intensity (tuneable white) – in schools can lead to improved performance in exam situations, have a calming effect or support the immune system in other situations. This trend is currently driven primarily by technology and marketing. Clear specifications for practice are still lacking.

Nevertheless, it is clear that the ***future of lighting lies in intelligent and adaptive systems*** that can respond to changes in the environment (weather, time, occupancy) as well as to individual needs (personalized lighting). This requires deeper user integration. Enablers are additional sensors and smart LED drivers, especially IoT-enabled products that provide the appropriate functionalities and can also network with other devices and systems. For networking with other systems at the building or city level, smart devices with optimized algorithms open up new possibilities for lighting control. Possible new service options go beyond pure lighting and the lighting network becomes an access portal for other things on the internet – such as the basis for M2M (machine-to-machine) communication.

National Highlights

Smart lighting and networked lighting systems are not

only significant for HCL. In general, networking in the sense of IoT is an additional benefit that modern lighting systems can offer to the user. In this context, research in Austria, which is strongly application-oriented, ***focuses on networking, integration and miniaturization of LED drivers.*** V-Research is therefore working together with Tridonic, the European market leader, to develop new generations of IoT-enabled smart lighting devices.

Integration and miniaturization of wireless IoT functionality

A key development step for networking luminaire systems and for smart lighting applications is the integration of wireless circuits and interfaces on an LED driver board. Different modules were investigated for their integration possibilities and strategies were worked out for complete integration for the development of a new wireless system (Wireless Reference Platform). .

The first integration step was the transfer of the conceptual wireless systems into integration-capable assemblies,

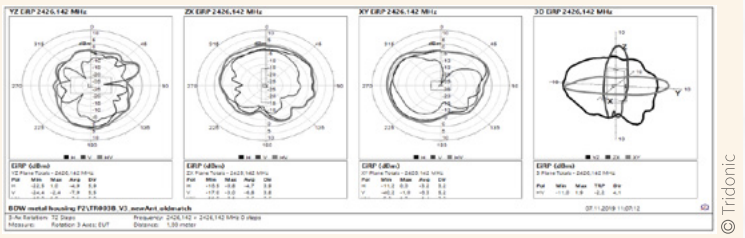


Figure 2: The radiation characteristics in the metal housing were optimized until they corresponded to those in plastic housings.

whereupon four modules for different LED drivers were created and released for production. Compatible antenna systematics for metal packages in LED ballasts were created and verified based on a BDW LCA 50 W 350-1050 mA LP PRE prototype. The range requirements were met by achieving a similar omnidirectional radiation pattern as LED drivers in plastic packages, which is typically >30 m in field tests. With the developed measures, a reduction of the component and cost share for wireless communication in LED drivers was achieved. The size of the chosen "Wireless Reference Platform" with an original volume of 2.1x4.0x1.6 cm3 was reduced to 1.27x2.00x1.6 cm3, a reduction of 70 %.

Free-form optical microlens films

Compact, cost-effective, efficient optical systems that meet the demands of modern lighting technology, and HCL in particular, are a key issue for Zumtobel, the European market leader in luminaires and lighting systems. As part of the international EU project Phabolμs, one of the company's use cases serves as an example of

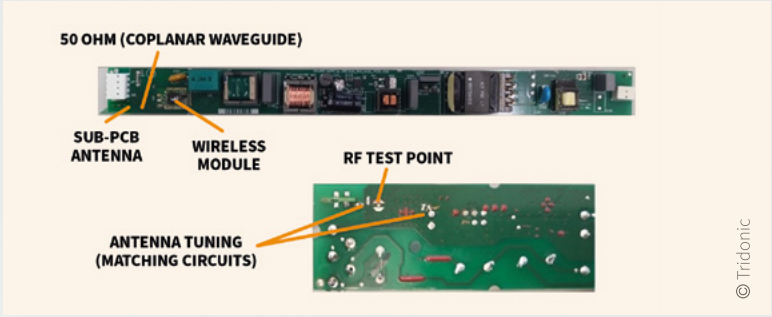


Figure 3: Overview Wireless System for use in metal housing.

the successful testing of the roll-to-roll (R2R) pilot line for the production of free-form micro-lens arrays (FMLAs).

Already in the first year, in cooperation with the project partner JOANNEUM RESEARCH, it was possible to develop a useful alternative to the bulky and expensive faceted reflectors that have been common up until now, confirming the research and development direction taken. The full potential of these technologies has not yet been exhausted with the given task. The technology has been in use since the beginning of 2021 in the world's first continuous light line that meets the highest architectural and lighting requirements, in Zumtobel's SLOTLIGHT infinity, which has been tried and tested since 2015. The product's advantage is its versatility. The light lines, which can be up to 50 metres long, no longer have any seams and even around corners, they shine with uniform brightness.

In Focus

The increasing demands of lighting systems and smart lighting, in particular LED drivers and their power electronics, go hand in hand with the desire for miniaturization. This requires the use of highly integ-



Figure 4: Development of power-saving circuits for the lighting sector.



rated components. Added to this is the desire for greening and ***optimization for a sustainable circular economy***. Reliability and service life as well as the integration of additional intelligence are crucial issues. For optical systems, the development of cost-effective, sustainable, efficient and yet compact solutions is of significant importance to fully exploit the potential of current and future light sources. Research and development of new production methods and tooling applications are considered key to meeting these demands. In this context, digital engineering and the application and development of new, improved simulation methods and systems are of highest interest to research institutes and their industrial partners.

In addition to their importance for ***HCL and Smart Lighting***, many of the following technologies are useful in the field of agriculture and food production. In many urban regions, it is already a problem that there is not enough agricultural land available close to the city. A transition is taking place from traditional arable farming to vertical farming - growing plants in high-rise buildings - using artificial light rather than sunlight. In order to save energy, however, the artificial light should, as far as possible, contain only those spectral components that the plant actually needs for photosynthesis and for the production and storage of flavour substances and essential nutrients such as vitamins and trace elements.



Figure 5: HCL artificial light solution (2200 K to 5000 K) in Bartenbach's R&D building.

Free-form surfaces – optics for lighting technology

In modern lighting systems, the emitted light from the light source will be better utilized by newly developed free-form optics, whereby the light is focused precisely on the desired area and as little stray light as possible escapes into other areas. The illumination will be as homogeneous as possible and ideally have exactly the same brightness in the centre as at the edge, but this requires very complex optics. The structure sizes in free-form facet technology are therefore becoming smaller and smaller and are approaching the micrometre range. These facets can be applied to reflective as well as refractive surfaces or optical interfaces. Thus, we find ourselves in the transition zone between ray optics and wave optics and the calculation and fabrication of such optics requires new methods.

Specifically, the extension of simulation and calculation methods to the transition zone between ray and wave optics is required. In addition, the use of new methods (e.g. photon mapping), will be better tailored to the photometric tasks. Manufacturing techniques also need thorough adaptation to new requirements. Current injection moulding techniques are reaching their limits. New mould manufacturing methods or fundamentally different manufacturing processes, such as 3D-2Photon Printing for masters, or R2R will be necessary.

Nanostructures for optical interfaces and surfaces

By means of nanostructures on optical surfaces or interfaces, wave-optical effects are used. They are for instance applied to create spectral mixing or to reduce unwanted surface reflections (e.g. with the so-called "moth-eye effect").

Structured surfaces, as in the case of "diffuser foils" with microstructures, can be used to selectively expand directional light, for example into a square or elliptical distribution. Preferably, the production is carried out with role-to-plate (R2P) or R2R processes.

Further Photonics – technologies for lighting engineering

Due to the wide range of applications, numerous other technologies are of great importance – which also results in a wide field of research topics. Some are mentioned below:

- "Thermal smoothing" of optically effective surfaces or interfaces by treatment with lasers of different wavelengths
- Highly reflective or reflection-enhancing coatings on glass, metal, polymethyl methacrylate, etc. (e.g. on feather-hard aluminium for high-quality louvers in the visible light range)

- Switchable liquid crystal films for artificial lighting and glazing applications
- New materials for optical purposes (e.g. PMMA with a modified spectral cut-off, better UV stability, lower dispersion, etc.; or the addition of nano-particles to produce daylight-like Rayleigh scattering)
- Colour conversion techniques (phosphors) for LEDs
- Printed circuit board (PCB) developments
- Sensors for body, human, medical applications

Smart LED drivers

However, the benefit of smart lighting to provide ***more functionality and connectivity*** also tends to require more energy to operate. The challenge now is to reduce overall power consumption – especially losses in standby mode and in the partial load range of the devices. In addition, there is a need to miniaturize or increase the power density of LED control gear. To address the trend toward smaller, flatter form factors that approximate lamp geometry, research is being conducted on new LED driver platforms. The goals of this research for new platforms are to integrate functions into an ASIC to reduce component count and thus volume and to provide integrated drive and control for the most efficient switching power supply topology, depending on the application. It is also important to increase switching frequencies, specifically to minimize the volume of inductors and capacitors without compromising efficiency. New device technologies such as Gallium Nitride High Electron Mobility Transistors (GaN HEMTs) seem to be an ideal approach for this purpose, as they even promise to increase efficiency. However, in practice they also represent a challenge that requires corresponding research activities. The improvement of the integrated and isolated Digital Addressable Lighting Interface (DALI) voltage supply and the development of drivers for powers beyond 300 W with better system efficiency are still future research topics.

Light management systems

Due to the rapidly advancing development in the field of radio frequency microcontrollers, industrial research focuses on letting these devices take over more and more LED driver and sensor tasks. A key development step is the integration of radio circuits on an LED driver board. Tridonic is continuously investigating the integration possibilities of various modules and developing strategies for complete integration. The focus is on converting conceptual wireless systems into modules for sensors that can be integrated, compatible antenna systems for casted housings in LED drivers in particularly critical applications and reducing the component and cost share for wireless communication in LED drivers.

Simulations of EMC, driver and luminaire systems and the implementation of a Digital Twin

Successfully developed and validated simulation models of various systems already exist, however, there is a need to optimize the efficiency of the simulation workflows and the general approach. In particular, the potential to reduce the cycle time (pre-processing, simulation, post-processing) has not yet been exhausted. It also makes sense to make existing simulation models universally available in a library.

One challenge is disturbance immunity (e.g. critical voltage increases on sensitive components due to lightning) as well as disturbance emission (e.g. disturbances emitted by the LED driver that feed back into the supply network). Simulation including software-assisted semi-automated optimization is desirable to shorten the time-consuming process. Research aims to further develop modelling approaches for the filter elements required for this purpose. Significant progress is expected through more detailed modelling of PCB data and nominal and parasitic component properties. The resulting significant increase in the validity of simulation results will help to reduce the relative deviation between simulated and measured disturbance to ≤20 %.

The exciting research area of the "digital twin" supports ***life cycle management***, but also suggests more efficient, new solutions in early phases of lighting system product development. For this purpose, it is indispensable to develop a concept that combines the advantages of the "digital twin" with the extensive and well-founded simulation and modelling knowledge specific to the requirements of the lighting industry.

Integration and miniaturization

For LED light sources, the race for the highest efficiency has slowed down dramatically and is no longer the main focus in development. In addition to further improvements in service life, there is still growth potential for LED light sources, primarily in the area of HCL and LED modules with integrated, additional functionalities. Since luminaires are ubiquitous in many infrastructures, they can serve as nodes in IoT topologies and thus ensure short distances to the individual objects. This can minimize the transmission power re-

quired and increase the battery life of networked objects. By means of new technologies such as LiFi, the light emitted by the luminaires will itself become the communication medium in the future. Lighting can also make an essential contribution in terms of 6G backscatter technologies for communication through backscattered visible light communication and sensing.

LED light sources are always supplied with a constant voltage or constant current via electronic drivers, regardless of whether they are housed in a separate package or integrated into the light source. Since a microcontroller is usually already included, which also acquires and processes sensor data, additional functionalities can be implemented with comparatively little effort. It is only logical, for a rapid expansion of functionality with respect to HCL, to build on an existing integrated tuneable-white concept, in which the colour temperature can be adjusted by utilizing at least two light sources of different colours. Additional sensor and, if necessary, emergency lighting functions can further increase the level of integration.

The application of luminaire-integrated drivers is limited despite a plug 'n' play installation. For a consistent smart luminaire concept, external driver concepts are desirable for instance for smaller downlights, freestanding luminaires, linear and area luminaires. The sensors with receiving parts must be located on a separate "subprint", as special materials are required as substrates. The digital output signal represents an optimized solution in terms of robustness.

Optimized, compact multisensor solutions may also be useful for other applications. Results from sensor data and the lessons learned from a pilot installation suggest further exploration of different use cases and operating conditions. The main criterion is to process the sensor-generated raw data to provide more meaningful information for administrators/users/consumers/customers of the lighting network. Such information could be the actual occupancy information of workstations or meeting rooms, their noise levels, or the maintenance of the network and the operability of the luminaires, to name a few.

Often, data is also needed from sensors that cannot be integrated into a luminaire. This data should nevertheless be available in the same network in order to be able to implement various controls in the building automation system. To overcome these obstacles, it is necessary to use existing sensor solutions (e.g. room temperature, CO_2 etc.) and integrate them into the existing network.

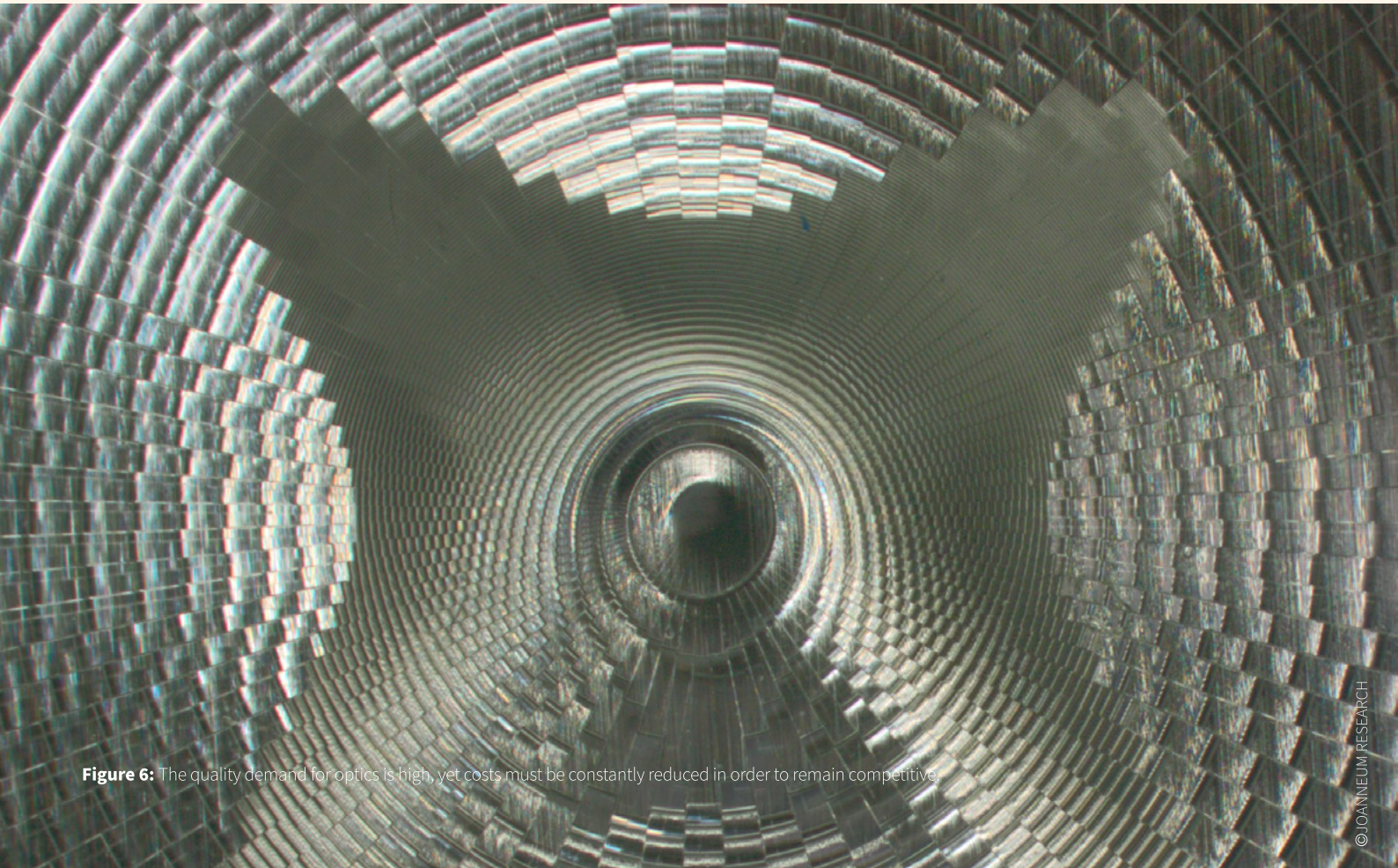


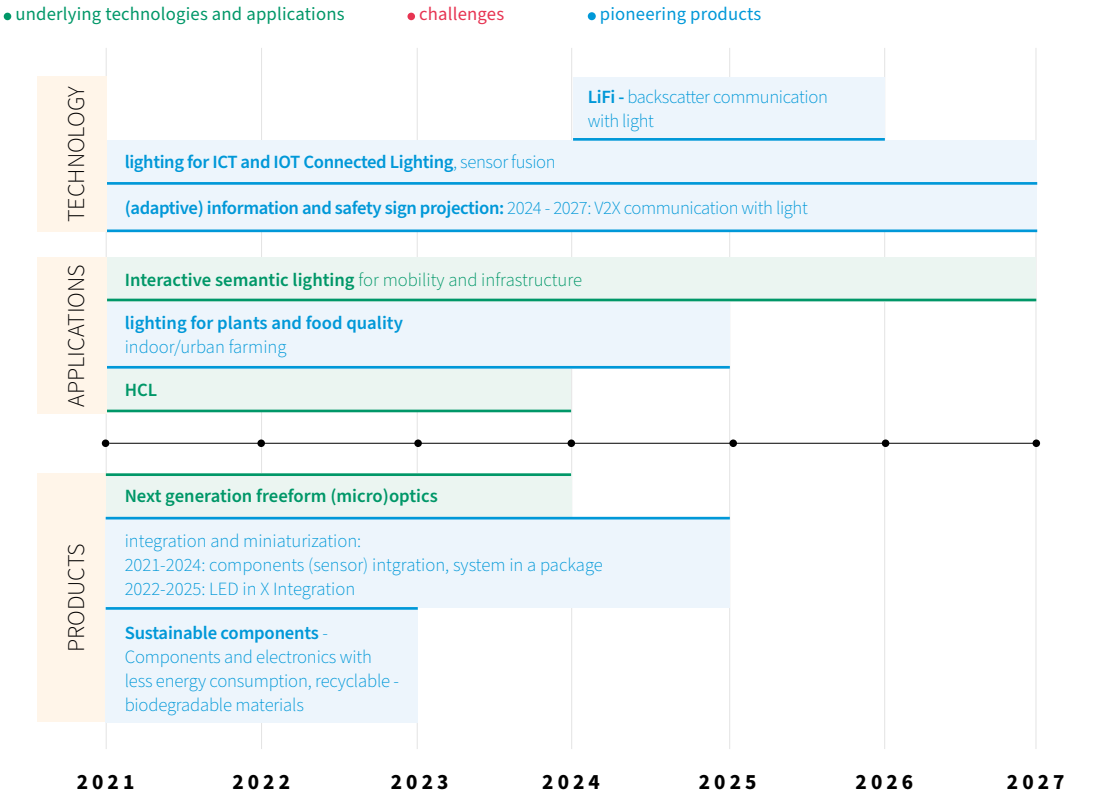
Figure 6: The quality demand for optics is high, yet costs must be constantly reduced in order to remain competitive.

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Statement

While the public perception used to focus on the energy-efficiency of lighting, the focus is now more on ***comfort, well-being and health*** of the inhabitants. There is still a lot of need for research in this area and it is a unique opportunity for the lighting industry to strengthen the status of light in society and to improve people's living conditions in the long term with HCL, Smart Lighting or Horticultural Lighting. ●

TIMELINE



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HCL, through flicker-free light adapted to needs, increases the well-being of end users. Higher integration density with fewer components lead to longer life and less electrical waste. Sensor technology and integration into building management systems optimize the overall energy management of the building. Predictive system maintenance and automated adjustments extend useful life through continuous, autonomous improvement. Modular and updatable communication modules allow universal application with easy and resource-saving reusability. Optimized simulation methods increase robustness and reduce failures and thus replacement of equipment. Thanks to energy-efficient lighting, around 3,742 TWh can be saved worldwide each year, which corresponds to a CO_2 saving of 1,500 megatons. In addition, spectral control of plant growth can adapt agricultural production to fluctuating daily demand (e.g. flowers for Valentine's Day) and thus also improve the CO_2 balance, increase the number of harvests and their yield and quality.

Connected Mobility, Transport and Safety

The mobility of the future is on the verge of its biggest revolution yet. ***Autonomous driving, connectivity and monitoring*** are becoming increasingly important and are driving new concepts and technologies. In addition, the individual mobility of the Austrian population is steadily increasing, with not only the number of passenger kilometres travelled in private cars rising, but also strong growth in local public transport (ÖPNV). Austria leads the EU in terms of rail kilometres per person.[1]

This development brings challenges and opportunities in equal measure to make Austria's roads, tracks and airspace safer, more efficient and more sustainable. Due to its complexity and ubiquity, mobility has become a central point in Austrian everyday life with complex effects on society.

From a global perspective, the steady increase in individual transport has resulted in the rise of energy demand in the transport sector. Today, 30 % of Austria's greenhouse gas emissions[2] are attributable to the transport sector alone, but also other harmful emissions such as NO_x or "particulate matter" are caused by traffic. According to a study by the Federal Environment Agency,[3] PM2.5, a specific type of particulate matter, reduces life expectancy in Austrian cities by up to 17 months. Thus, the drastic reduction of emissions caused by traffic is unavoidable in order to achieve national climate goals and a healthy society in the long-term.

All sectors of transport, including rail, can benefit significantly from photonic innovations: Advances in optical sensor technologies such as ***flash-/LiDAR*** and the further development of optical data processing systems are bringing autonomous driving within reach. Innovative concepts for minimizing vehicle consumption, alternative energy sources and propulsion systems aim to reduce negative impacts on the environment and society while increasing safety. In connection with safety aspects, especially modern LED- or laser-based headlights are worth mentioning, as they are already helping to make our roads safer. Photonic technologies



Figure 1: Fibre optic Distributed Acoustic Sensing enables vehicle tracking. Condition monitoring of infrastructure and natural hazard detection over a length of 50 km with only one fibre optic cable and sensor.

© DAS

allow seamless environmental monitoring in diverse environmental conditions or highly accurate real-time detection and tracking of trains, for example through Distributed Acoustic Sensing (DAS), which will complement future rail safety concepts. Unmanned Aerial Vehicles (UAVs), often colloquially referred to as drones, can reliably warn of potential hazards in real time.

National Highlights

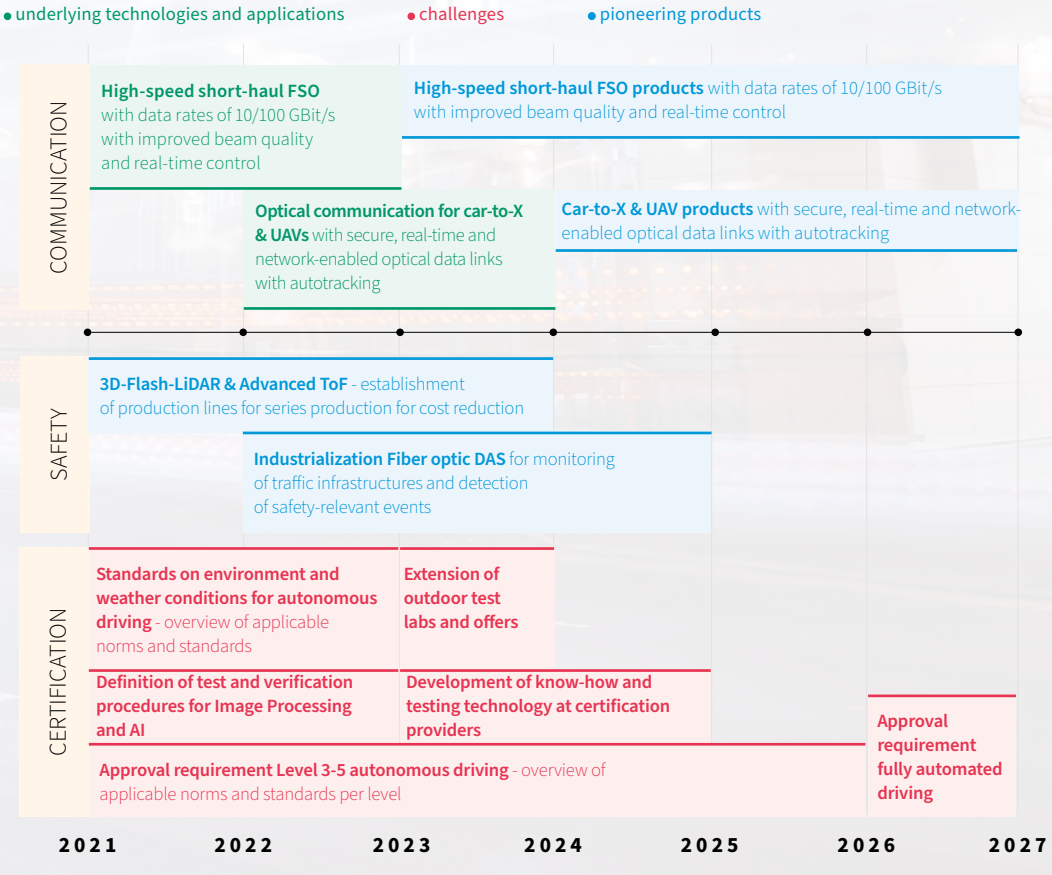
The lighting sector of the European automotive industry will experience strong growth in the upcoming years, mainly due to the presence of major manufacturers. The lion's share can be attributed to LED lighting, as long service life and low energy consumption with comparatively high performance offer an attractive alternative to halogen and xenon headlights.[4] The Lower Austrian original equipment manufacturer ZKW, and also HELLA, a company with production headquarters and a long tradition in Austria, have been able to record a breakthrough in terms of road safety. As a production location, Austria will be able to benefit greatly from this development.

Matrix LED headlights

LED headlights have been an exciting area of research in the automotive industry for years, as the integration of an LED headlight module combines design flexibility with miniaturization and maximum energy-efficiency. However, it was not until 2005 that the first all-LED main headlamp was presented, which achieved comparable results in terms of light output to commercially available xenon headlamps. Since then, the use of LED lighting concepts in the automotive industry has developed rapidly.

Matrix LED headlights enable glare-free high beam by selectively excluding objects, which means that oncoming vehicles are not dazzled while at the same time the remaining road space with potential obstacles is still well illuminated. A system without moving mechanical components that also guarantees maximum reliability with low maintenance was presented by HELLA. The LEDs of the five 5-chip LED reflectors can be controlled individually and can thus be dimmed up or

TIMELINE



down as required. The everyday relevance of this new technology becomes clear when the stress levels of car drivers are examined. More than half of all drivers feel stressed by poor visibility.[5] Therefore, the safety of all road users can be increased through excellent illumination of the road and a reduction in the stress level of drivers.[6,7] Driver in-cabin functions are realised by ToF-cameras. For example, the camera can track the eyes and their movements and thus signal fatigue or distraction to the driver. In addition, they enable intuitive operation of navigation or radio, so that the driver's attention is not diverted from driving itself.

Laserlight

ZKW recorded another success with the introduction of ***Laserlight***, a new high beam technology based on the use of laser diodes. It not only excels with its small size and the associated design flexibility, but also impresses with an even higher light intensity combined with lower energy consumption than the already extremely efficient LED headlights. The main beam range has been increased to 600 m for Laserlight, which is three times the current standard, thus further enhancing safety in night time traffic.[8]

In Focus

Austrian competences range from original equipment manufacturers in the automotive industry to competitive research projects at domestic universities and research organizations. Photonic technologies have greatly changed the image of modern traffic, the transport industry and the security sector and have the potential to shape it in the long term. For example, the development of unmanned aerial vehicles has evolved in recent years to a technology with a broad range of applications.

Photonics supporting emergency services

In airspace, photonic technologies bring new possibilities for a wide range of applications. UAVs (drones), in combination with state-of-the-art photonic components, enable the analysis of unknown terrain to support emergency services in the event of a crisis or disaster, for example, large-scale landslides. Laser measurements with LiDAR technology can provide an up-to-date and highly accurate 3D terrain model, and will be able to provide the models in real time in the future. With modern ***LiDARS, combined with signal processing***, vegetation-related visibility problems no longer exist – hidden paths, hidden torrents and impassable roads can be detected efficiently and quickly, significantly increasing the safety of emergency services. Furthermore, specific potential sources of danger, such as exposed radioactive substances or spontaneous gas leaks after an earthquake or accident, can be efficiently located and identified by additional sensors.

The essential part is high-quality 3D terrain data. This can be generated by laser scanners or novel 3D 360° panoramic cameras (TUCO-3D). Equipping the UAVs with the appropriate systems enables the creation of an interactive map for visualization on a tablet within a very short time.

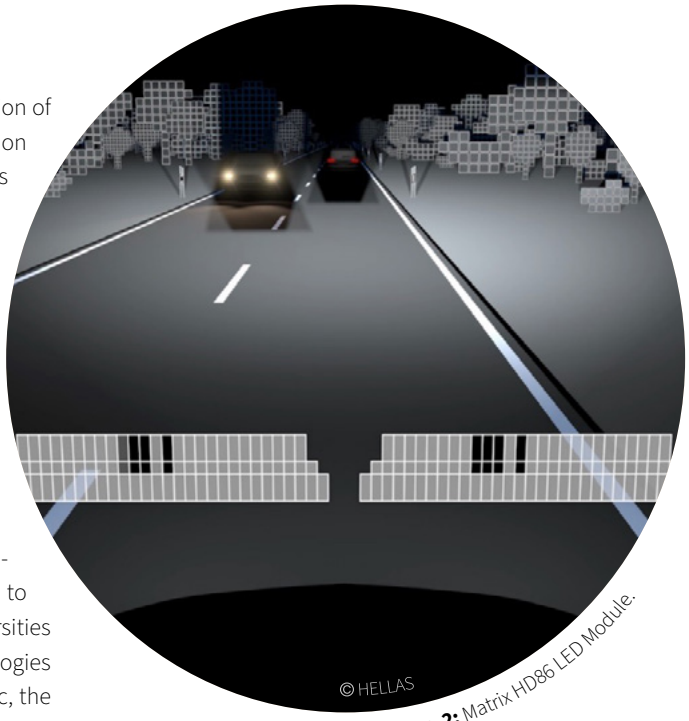


Figure 2: Matrix HD86 LED Module.

The live transmission of data between individual drones and the ground station represents one of the greatest challenges in the field of UAVs. One promising option is the use of ***optical directional radio using Free Space Optics (FSO)***, which is considered to be particularly attractive due to its high data throughput, long transmission range and negligible interference. By using FSO, the communication network between UAVs can operate completely autonomously, eliminating interference from alternative frequencies, which would otherwise need to be considered in the shortwave range.

However, FSO-links in free space can be limited by atmospheric turbulence, whereby the reliability of the network is reduced. Thus, the design of the network architecture is essential to achieve high network resilience. Resilience in this context refers to the ability of a network

topology to withstand link failures. To solve this problem, two Network Resilience Aware Topology Formation (NRATF) methods, i.e. centralized-NRATF and distributed-NRATF, are studied to efficiently solve the topology design problem and ensure failure-free communication between drones.

3D LiDAR and CBRNE sensors (chemical, biological, radioactive, nuclear or explosive) generate a multi-dimensional view. The combination of all available measurement tools and values generates a comprehensive set of information that can pinpoint the exact location of radioactive sources via the determination of key parameters. Furthermore, the benefits of real-time situational awareness enable localization within one minute. By combining the radioactivity measurement with 3D terrain maps, the contamination can be modelled. A reliable ground model is created using high quality lasers. Fast scans provide complete results after 400 s, with an accuracy of about 1 m and an area of up to 500x500 m. This intelligent detection of radioactivity clearly displays the results and measurements in a zoomable and rotatable map.

AIT, Austrian Institute of Technology, is working within the KIRAS projects "Durchblick"[9] and "UAV-Rescue"[10] to make ***real-time information from LiDAR data available to first responders***, enabling early detection of hazards and increasing the safety of emergency workers.

From Advanced Driver Assistance Systems to Autonomous Driving

Autonomous vehicles will enable more Austrians to actively participate in social life, as drivers will no longer be necessary. Currently, commuters need an average of 29 minutes each way to and from work.[11] The advantage for Austrians is that they can make constructive use of commute times, which in the end significantly shortens the working day. Autonomous driving, as the key to safe and ecologically compatible individual transportation, is described in six levels depending on the participation of the driver (Fig. 3). Systems that support partially and highly autonomous driving are already in standard use today as so-called autonomous driver assistance systems (ADAS), for example lane-keeping systems, braking and parking assistants. By the time fully autonomous driving is realised, a large proportion of traffic accidents could already be prevented by implementing ADAS.

High-performance wireless connectivity without downtime further enhances road safety through seamless traffic monitoring and early hazard detection. Following the rise in the number of private cars, global traffic volumes are also expected to increase. Since autonomous vehicles communicate with each other and with their environment, optimal acceleration and braking procedures can be implemented, thus maintaining optimum traffic flow. A reduction in traffic-related emissions can be expected due to the higher efficiency of driverless cars.

Frequency Modulated Continuous Wave LiDAR (FMCW-LiDAR), flash-/LiDAR and ToF play an important role in the development from ADAS to autonomous driving. ***Photonics provides the technological backbone of many ADAS components.*** Camera and radar sensors or LiDAR systems support drivers and help to avoid errors or, subsequently, accidents. Step by step, increasingly sophisticated ADAS components are finding their way into the new models of major automobile manufacturers, with communication between two vehicles (C2C) or with the environment and infrastructure (Car2x) forming the basis.

Currently, networks for ADAS in cars still face significant challenges in terms of data rates, complexity and weight, security and interference with direct impact on reliability, safety, driving behaviour and fuel consumption. Autonomous vehicles are currently designed as autonomous systems, relying solely on on-board sensors. This type of

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In the area of connected mobility, transportation and safety, photonics will be able to contribute to the conservation of resources, especially by increasing energy-efficiency and reducing emissions. The reduction of emissions caused by individual traffic will be enabled, in particular, by autonomous driving. Audi already claims to achieve a saving of up to 0.7 litres per 100 kilometres through its current "adaptive cruise control" (avoiding excessive acceleration and braking, maintaining distance, observing speed limits etc.). The University of Michigan predicts a 16 % reduction in energy consumption and emissions when eco-driving programs are taken into account. Expectations are even higher for fully autonomous driving. A modern, well-monitored rail network also helps to reduce impact on the environment and conserve resources by allowing more trains to run safely on the same rail network, and small, lightweight UAVs can replace large reconnaissance helicopters in some applications.

system structure produces massive amounts of data, which will continue to increase as more ADAS components are implemented to support and ultimately provide driverless control. Photonics is seen as an enabler here, because it enables the necessary computing power, takes up minimal space and provides efficient data transmission using FSO. As explained in the ICT chapter (page 27), photonics offers even more tools to solve these challenges.

Seeing in the dark

LiDAR, a laser-based measurement method, is considered a promising foundation of many ADAS applications. It was developed during the Apollo space program to map the surface of the moon. Thus, LiDAR per se is not a completely new technological development, but only now are companies able to work with sufficient precision to produce high-quality 3D images, which are absolutely necessary for autonomous driving. Combined with high-resolution cameras and conventional radar technology, LiDAR will make roads safer. European automotive manufacturers and their network of photonics industry suppliers – including many start-ups and SMEs – are making rapid progress.

Recent advancements in photonic technologies offer the opportunity to overcome the previous challenges of seamless environmental monitoring and the resulting huge amounts of data created. Software algorithms, intelligent image processing and automated driving equipment, in combination with flash-/LiDAR and ToF, will take autonomous driving and road safety to the next level of development.

LiDAR is characterized primarily by its ability to quickly detect moving objects regardless of applicable lighting conditions, while maintaining high resolution and detail. However, the complex optics of LiDAR, due to its size, moving components and mirrors, is currently the biggest hurdle on the way to commercial use in the automotive industry. A breakthrough has been achieved with 3D flash-LiDAR. This overcomes the usual limitations of a laser needing a very clear field of view. Stop signs, pedestrians and lampposts can thus be easily detected even in twilight, darkness, dust, fog, rain or other unfavourable weather conditions. The Austrian research activities are making a significant contribution to the introduction of series production by establishing production lines and thus reducing costs.[12]

Well-protected infrastructure

There are currently a large number of different sensor systems for monitoring traffic infrastructure and detecting safety-relevant events at their perimeters. Current sensor systems are similar, in that the measurement and thus the monitoring can only be made selectively (e.g. axle counters) or on short sections (e.g. with a video camera) but not without gaps over large areas in the order of kilometres. For gapless condition, traffic and safety monitoring, sensor technology is required that enables measurements over wide areas.

Fibre-optic DAS is the solution to the above problem, and railroads in particular, as a major contributor to decarbonisation in transport, will benefit. The reduction of initial costs and additionally a significant reduction

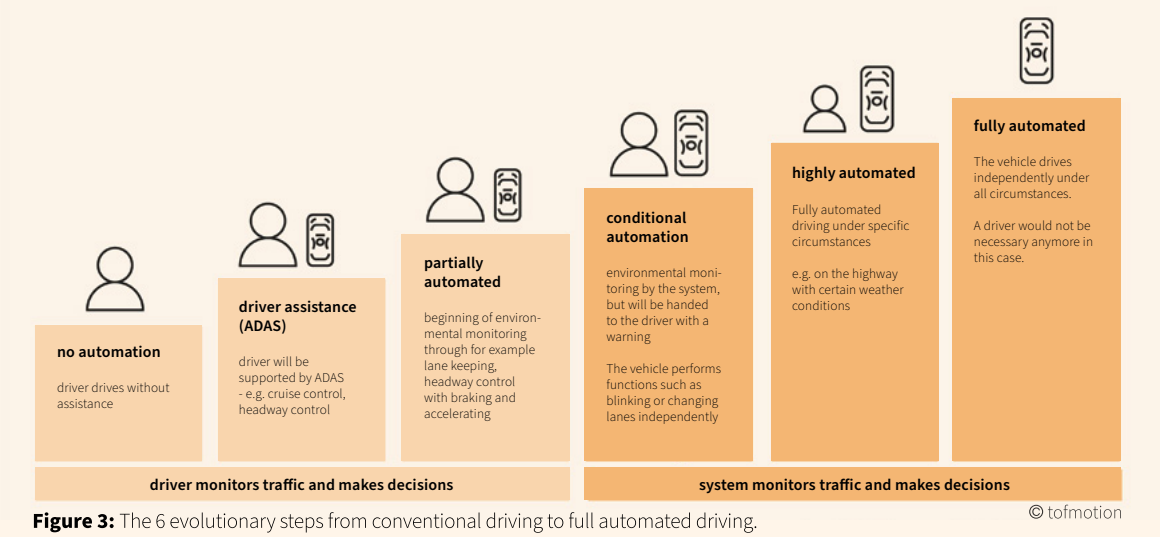


Figure 3: The 6 evolutionary steps from conventional driving to full automated driving.

© tofmotion

of maintenance costs by using one sensor instead of the many individual sensors installed along the railroad infrastructure, and the acquisition and monitoring of measurements by a single existing fibre optic cable are only two of the main advantages of DAS. ***Seamless monitoring of infrastructure, highly accurate real-time detection and tracking of trains*** with DAS will thus complement future rail safety concepts.

DAS is a fairly new technology that allows large areas to be measured and monitored over long distances without gaps. With an already laid single fibre optic cable of up to 50 km and with only one active device, it is possible to monitor very large infrastructures or perimeters such as vehicle tracking, condition monitoring of infrastructure, natural hazard detection and incident detection. The only active component in a DAS monitoring system is the "interrogator" device used to generate the laser pulses for measurement, as well as the evaluation hardware. This allows all active hardware to be located in one place, which makes such a system relatively low maintenance compared to other active sensor technologies.

Thus, the AIT Austrian Institute of Technology, together with NBG FOSA and Dr. Döller Vermessung ZT were already able to demonstrate simultaneous rock avalanche detection and train tracking with a single DAS system on a railroad line.

Statement

Autonomous mobility and transportation are significant trends and goals for the future. Photonics is a major contributor to achieving these goals. In order to develop and realize autonomous driving on road and rail, appropriate framework conditions are required:

For example, around 200 million test kilometres are required for the approval of a fully automated or driverless vehicle (Fig. 3). This is due to the complexity of vehicles, their various sensors and the wide variety of scenarios that arise in road traffic as well as from prevailing environmental conditions. In recent years, suitable test tracks have been created in Austria for this purpose, for example DigiTrans and ALP. Lab for public passenger and goods transport or Open.Rail.Lab for autonomous trains. Further, more in depth, auditable and comprehensible AI and simulation scenarios also have to be created, such as the simulation of ToF cameras under environmental conditions in the LIGATE consortium.[13] This requires early collaboration between innovation drivers and standardization institutes to ensure that innovations are not only available but also usable. ●

Source:

[1] EU-Kommission, VCÖ 2020 | [2] Klimaschutzum Beispielericht 2020, Umweltbundesamt; Werte mit EH | [3] Abschätzung der Gesundheitsauswirkungen von Schwebstoff in Österreich, Umweltbundesamt 3005: https://www.umweltbundesamt.at/fileadmin/site/pubikationen/rep0020.pdf | [4] https://www.gminsights.com/industry-analysis/automotive-lighting-market | [5] Studie: Frost & Sullivan | [6] https://www.hella.com/hella-com/de/Scheinwerfer-620.htm1 | [7] https://zkw-group.com/home/produkte-und-innovationen/fernlicht-ohne-blenden/ | [8] https://zkw-group.com/home/produkte-und-innovationen/eine-leuchtende-innovation/ | [9] https://www.kiras.at/gefoerderte-projekte/detail/d/durchblick/ | [10] https://www.kiras.at/gefoerderte-projekte/detail/d/uav-getragene-sensorik-zur-ki-basierten-unterstuetzung-von-rettungsmissionen/ | [11] Statistik Austria: Erwerbstätige nach Pendelziel 2018 | [12] ERA-NET Photonic Sensing Dissemination Event, Dr. Bernhard Schrenk | [13] https://www.ligateproject.eu/consortium.html

Photonic Quantum Technologies

Very few users of modern information technologies are aware that their basis is quantum physics. The properties of the materials and the functionality of the semiconductor components used can only be explained, modelled and optimized using quantum theory. However, the developers of classical information technologies benefit from the fact that the bizarre-seeming effects, the actual quantum properties, remain well hidden and disappear at normal ambient temperatures and dimensions of the components. However, the relevant region of a current transistor is only about eight nanometres thick, which corresponds to about 35 atomic layers. This takes us into areas where quantum effects could play a role.



© Dieter Kühl, AQT

Figure 1: Quantum computer from AQT.

Conversely, it has been clear since the beginnings of quantum theory that quantum physical systems consisting of several particles can only be calculated at great expense using conventional methods of numerical mathematics, since immense storage space would be required. The largest supercomputers can currently fully simulate a system of maximum 50 particles. In applications such as the development of new drugs, to calculate the structure of complex biomolecules or catalysis, for example, for energy-efficient nitrogen fixation, it is extremely important to be able to accurately simulate much larger systems of quantum particles. As early as the 1980s, Richard Feynman therefore suggested that quantum systems should be simulated using other, controllable quantum systems. It was then even more surprising that in the 1990s it was discovered that so-called quantum computers can also solve certain tasks in classical computer science very efficiently, for example the decoding of information. However, eavesdropping is made impossible by another quantum technology: quantum cryptography, invented by Charles Bennett and Gilles Brassard in the 1980s.

This targeted exploitation of quantum effects is often referred to as the second quantum revolution, after the first enabled us to understand the materials and functions of devices. ***Austria has been a leader in basic quantum research since the early 1990s*** and has produced many "world records," such as the first quantum teleportation. On the other hand, the industrial implementation of scientific findings is only beginning slowly in Austria. Primarily through quantum cryptography, many connections to photonics arise, whereby photonic technologies are also essential in the construction of quantum computers, for example based on trapped ions. Further development of these photonic technologies thus goes hand in hand with the competition for supremacy in the quantum technologies of the future.

National Highlights

One of the first proposals for the realization of a quantum computer came from Peter Zoller and Ignacio Cirac at the University of Innsbruck[1] in 1995. Even though it was still a long way from practical realization, today the company Alpine Quantum Technologies (AQT) is building the ***first quantum computers ready for se-***

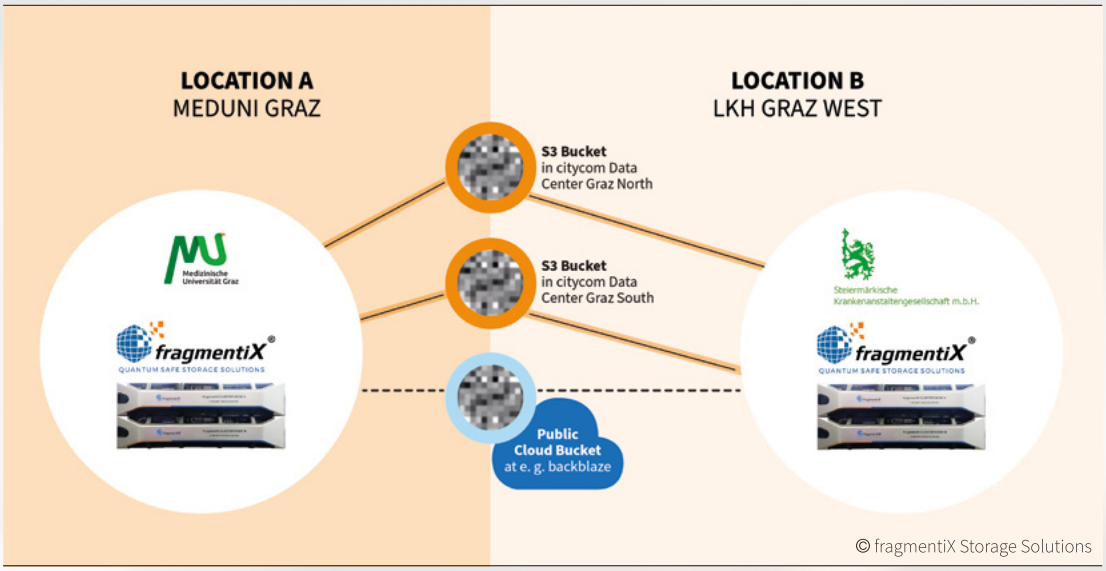


Figure 2: Schematic representation of the QKD network in Graz.

ries production with the core based on a few trapped atomic ions. The ions are held in an electric trap in a vacuum and cooled with lasers. Specially shaped laser pulses then perform the quantum gate operations and a series of gate operations forms the processing of the quantum information. Several photonic technologies are used in this quantum computer, narrow band lasers, optical waveguides, acousto-optic modulators and also the readout of the results is done by counting fluorescence photons. AQT was able to demonstrate that all this is possible within two 19" racks in early 2021 with a 50-qubit quantum computer, including precise control of the individual ions and the detection of a 24-qubit entangled state.[2] This puts Austria well ahead in the competition for application-ready quantum computers.

Securing medical and biometric data is becoming increasingly important. In Austria, the H2020 project "OPENQKD", coordinated by the AIT Austrian Institute of Technology, has now demonstrated for the first time how to secure this highly sensitive data during transmission as well as in (data) storage. The Medical University of Graz, together with the Provincial Hospital Graz-West, recorded slide scans from the pathology department for the purpose of digital diagnostics. These data were distributed in the fibre optic network of Graz-based Citycom Telekommunikation and stored in their data centres. The data was secured in the data centres by means of secret sharing. In this process, the data is divided into a freely selectable number of fragments according to algorithms developed by Adi Shamir in 1979. At the same time, it is also determined how many of these fragments are required to be able to read the original data again. A data leak in one of the data centres would thus not be a problem. The servers for secret sharing were installed by fragmentiX Storage Solutions in the Graz network and connected to the respective data storage and medical departments. In order to protect the data during transmission to the data centres, encryption based on quantum key distribution was also used. This exchange of symmetric keys, which is based on natural laws, is used to provide absolutely tap-proof encryption of the data via the optical fibre. The network in Graz consisted of a total of four nodes with 50 km of fibre links and was tested for three months in real operation.

Although diamonds are mainly known as precious jewels, they are finding their way into technology due to their transparency, outstanding hardness and extraordinary thermal conductivity. In photonics, diamonds are known for their colour centres, which have strikingly robust quantum states. These colour centres can be used in quantum communications,[3] but also function as highly sensitive ***quantum sensors,*** especially for measuring magnetic fields.[4] Such sensors can even measure the magnetic field of individual atomic nuclei, and are therefore of interest, for instance for microscopic magnetic resonance systems. With the help of Infineon's world-leading electronics development, a major step has been taken at the University of Vienna to miniaturize these quantum sensors and develop them into commercial components. In collaboration with SAL and Phi-

lips Austria, further approaches to system integration and commercial application are now being investigated.

In Focus

Quantum communication

Quantum communication deals with the ***transmission of quantum states for the purpose of information exchange.*** Since photons (individual light-particles), are particularly well suited for transmission, this field of quantum technologies is very closely related to photonics. Since photons behave according to quantum mechanical laws, new fields of application arise in quantum communication, such as ***quantum cryptography.*** There, it is possible to develop new cryptographic primitives that have increased security against attacks. The best-known example is ***quantum key distribution (QKD)***, in which a symmetric key is exchanged between two communication partners. This key can then in turn be used in a classic encryption method such as Advanced Encryption Standard. The advantage of QKD is that the key transmission is based on single photons and therefore provides security against all conceivable attacks as well as against attacks by a quantum computer, which can break the key transmission very quickly with the public key infrastructure currently in use. The fundamentals of QKD have already been well researched and there is now increased testing of the everyday suitability of this technology. For this purpose, prototypes and even commercial QKD systems are deployed in the field together with end users. Current

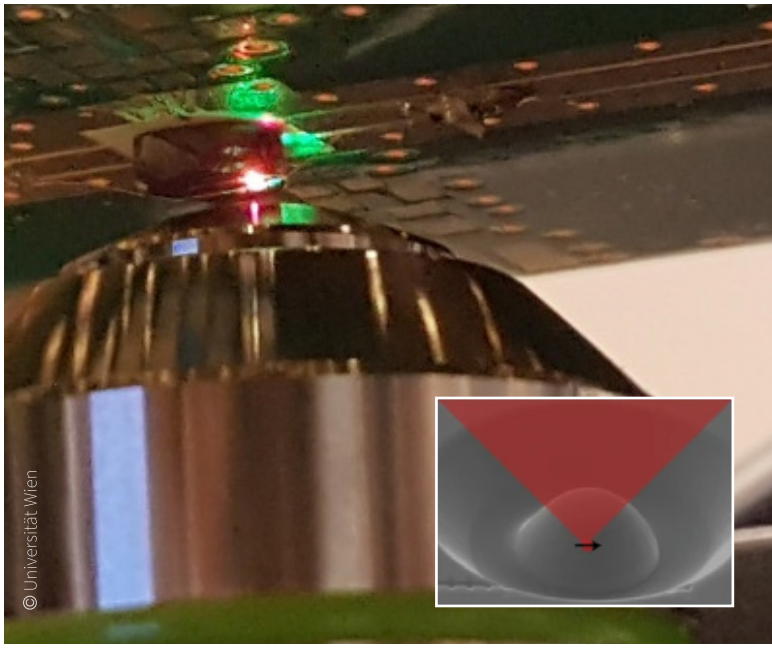
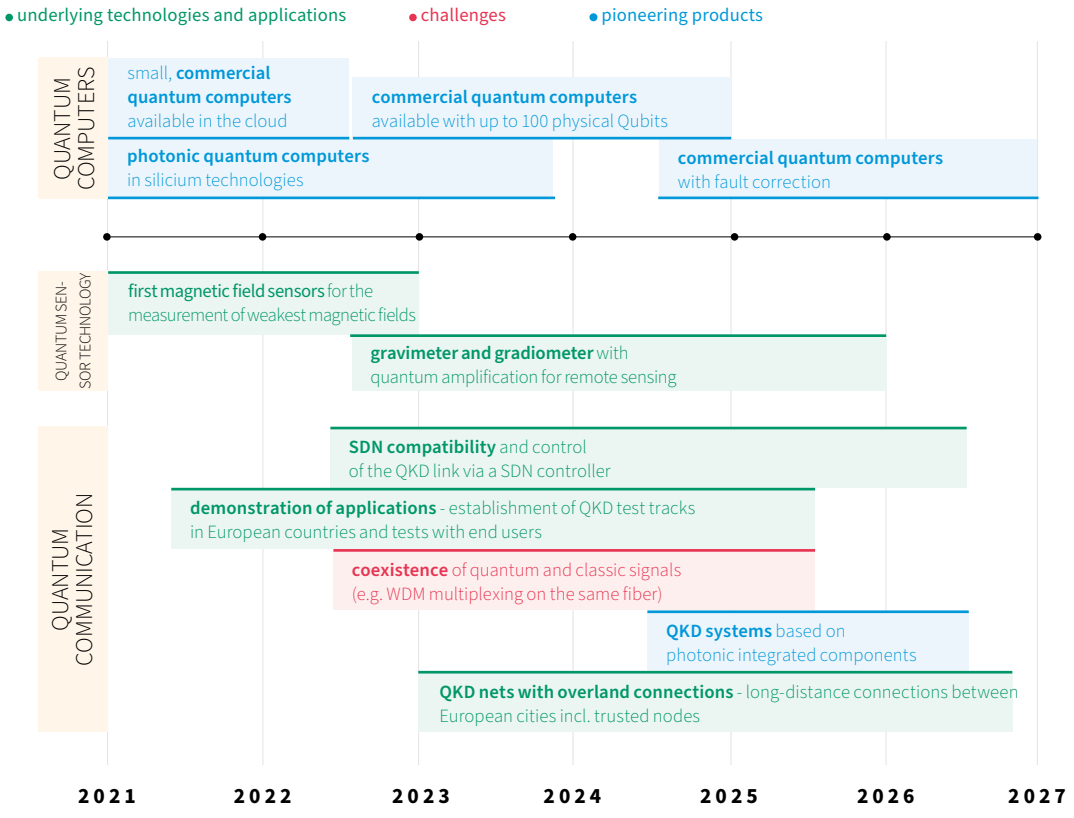


Figure 3: To increase the photon yield, microlenses (0.01 mm) were created directly above the colour centre in the diamond. Doped diamonds are integrated with microelectronic components for quantum sensing.

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QKD systems are based on discrete optical components such as lasers, phase and amplitude modulators detectors et cetera with a 19-inch form factor for installation in server racks. In order to further promote proliferation and also reduce costs, miniaturization of the electro-optical elements is necessary. In many laboratories, first steps are being taken to implement parts of a QKD system on photonic chips. In most cases, chips based on silicon, silicon nitride or indium phosphide are used to increase the symbol rate (>1 GHz) in the transmitter units, to reduce losses in the receiver units and generally to improve stability and connectivity to the electronic control units. One problem is still the miniaturization of the single photon detectors, since they are mostly based on (handpicked) avalanche photodiodes, which have to be well cooled to suppress the background noise and have a poor power balance especially at 1550 nm. The way out is provided by a special QKD implementation that does not rely on single photon detection. For the so-called CV-QKD (continuous-variable QKD), the key information is encoded in phase space, similar to quadrature amplitude modulation, and the quantum signals are measured using coherent detection. Synergies with classical optical communication are obvious and can help CV-QKD to become more widespread.

Another application of quantum communications that also benefits greatly from photonic integration is the ***quantum random number generator (QRNG)***. Simpler in design than a QKD system because transmission is omitted, a QRNG generates a flow of binary random numbers. The randomness is based on the intrinsic probabilistic description of quantum effects, such as the "which way" measurement of a photon at the beam splitter. Thus, it is not possible to predict or determine the sequence of numbers on the basis of additional measurements. The random numbers are therefore very well suited for cryptographic applications where very high unpredictability is required. QRNGs of a few millimetres in size can be fabricated nowadays on photonic chips.

The third application area in quantum communication is the ***quantum repeater***.[5] This is a communication link between two distant points where quantum mechanical

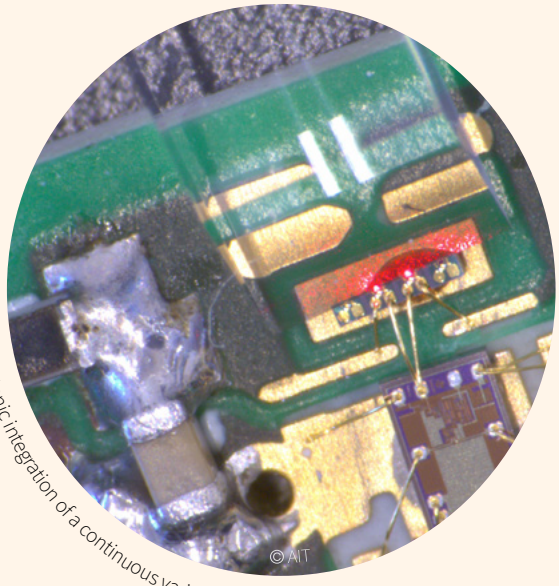


Figure 4: Photonic integration of a continuous variable quantum receiver.

information is transmitted. The advantage of this is that the state does not have to be measured and thus superpositions of states can also be transmitted. In addition to the entangled photons, a very important component of a quantum repeater is the so-called quantum memory, which must store the information of an incoming photon for a short time and then process it further. For this purpose, technologies from quantum computers and quantum sensors are also used, such as ion traps or colour centres. Quantum repeaters can be used to network quantum computers to enable joint computation across separate sites. Repeaters also provide a way to operate QKD over long distances (>500 km), since single point-to-point QKD links cannot span these distances due to losses in optical fibres. Quantum repeater research is strongly being pushed, but it is still at an early stage because the technology required is as costly as for a quantum computer.

Quantum computing

As described in the introduction, quantum computers promise to be able to ***efficiently compute important but previously almost unsolvable problems.*** They do this by making the basic unit of information not a binary bit, but a so-called qubit, which is a quantum mechanical two-state system that can assume continuous values

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Quantum technology opens up new possibilities in many areas. In the distant future, energy-efficient, small quantum computers could replace conventional mainframe computers, which would lead to a noticeable reduction in their CO_2 footprint. In addition, quantum computers also enable the simulation of previously incalculable quantum systems. Quantum computers could help to understand large molecules and their interplay in chemical and biological processes, creating new opportunities in the development of drugs or efficient catalysts.

between 0 and 1. In contrast to the previously pursued niche topic of analogue computers, several qubits can be in common superposition states – so-called entangled states. On the one hand, this makes the simulation of quantum mechanical systems difficult. On the other hand, it is a powerful tool if one manages to create and manipulate these states in a controlled manner. In a sense, the quantum computer thus computes innumerable possibilities simultaneously, and by using clever computational algorithms, one can take advantage of this parallelism. This does not mean that every type of computation is accelerated, but there are important use cases, such as searching in an unsorted database, factoring numbers and simulating relevant quantum systems, such as large biomolecules for drug development.

All leading industrial nations and some large international companies are therefore currently heavily investing in the development of quantum computers. Among the possible hardware platforms, three are particularly advanced: 1) superconducting quantum computers, 2) quantum computers based on ions and 3) purely photonic quantum computers. In both ion- and photon-based quantum computers, Austrian research and industry are in a globally recognized position. Superconducting quantum computers attracted attention mainly due to Google's demonstration of quantum superiority in 2019.[6] Quantum superiority means that a real-world quantum computer can solve a chosen computational problem significantly faster than any existing conventional computer and that this speed advantage increases for larger computations. Such quantum superiority was, with immense effort for the experimental implementation, also demonstrated in early 2021 by a Chinese research group for a purely photonic quantum computer.[7] In Austria, research on photonic quantum computers is being conducted at the Universities of Vienna and Innsbruck. To bring this research closer to application, the Christian Doppler Laboratory for Optical Quantum Computing was opened in 2020 under the leadership of Philip Walther.

Here, the required photonic technologies go hand-in-hand with the state of the art R&D of quantum computers. In particular, precise lasers, low-loss waveguide technologies in integrated circuits, fast phase and amplitude modulators and single photon detectors based on superconducting nanowires or avalanche photodiodes are needed to keep up with international competition.

Quantum sensor technology

In conventional, classical measurement technology, the sensitive measurement of very small quantities and weak effects often leads to effects of quantum mechanics, for example shot noise due to the quantization of a light field (photons). ***In quantum sensor technology, therefore, the main aim is to eliminate these obstructive effects*** or, conversely, to take advantage of the

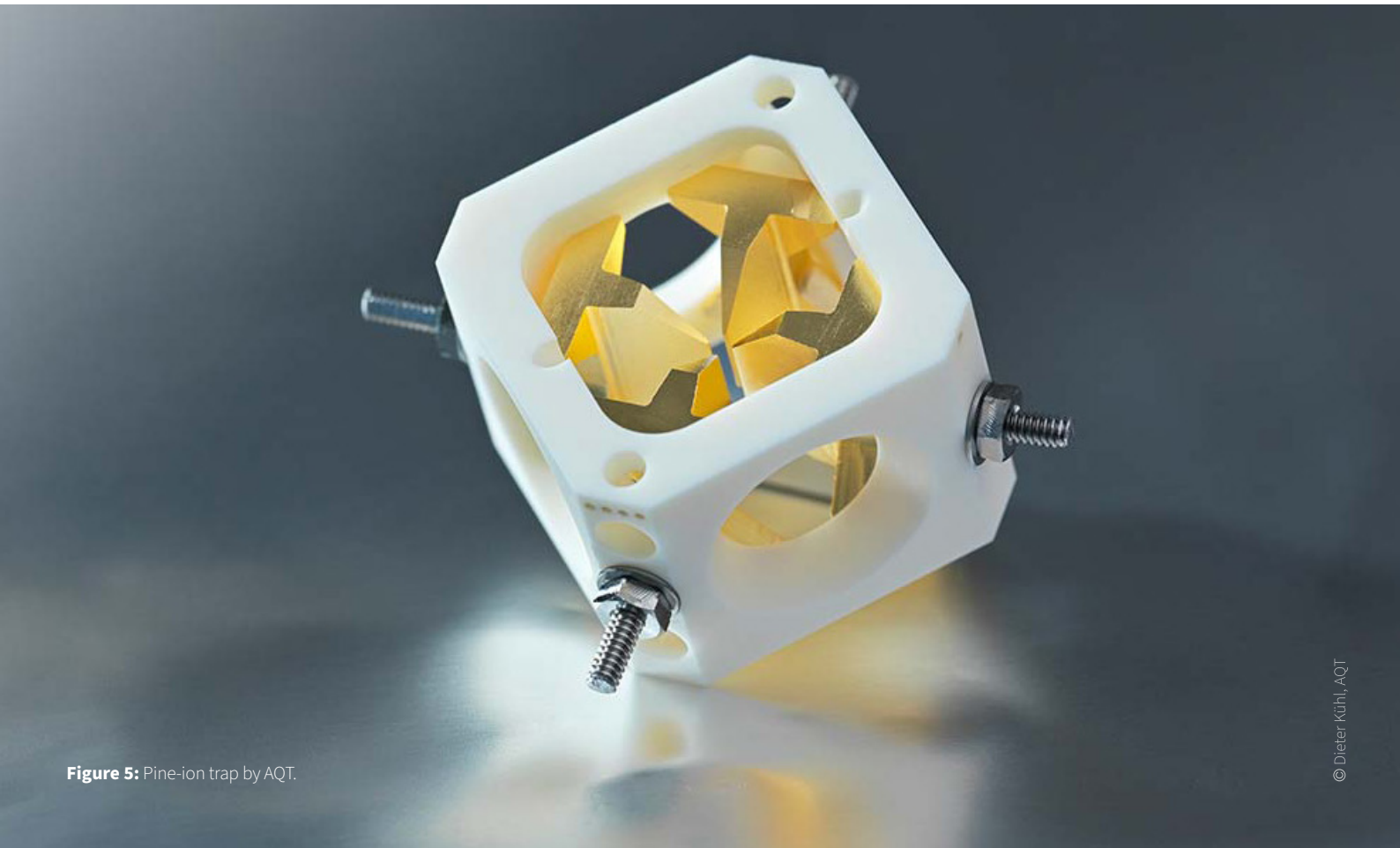


Figure 5: Pine-ion trap by AQT.

© Dieter Kühl, AQT

properties of quantum physics through targeted preparation of the quantum systems. The prime example is the idea of purposefully producing a so-called entangled state of many particles (e.g. atoms), which then react much mores sensitively to the measurand, such as an extremely weak magnetic field, than if the same number of particles were exposed to the measurand independently. Thus, theoretically, the scaling of the measurement accuracy with the square root of the number of experiments (= particles), which is well known from classical metrology, can be improved into a proportional

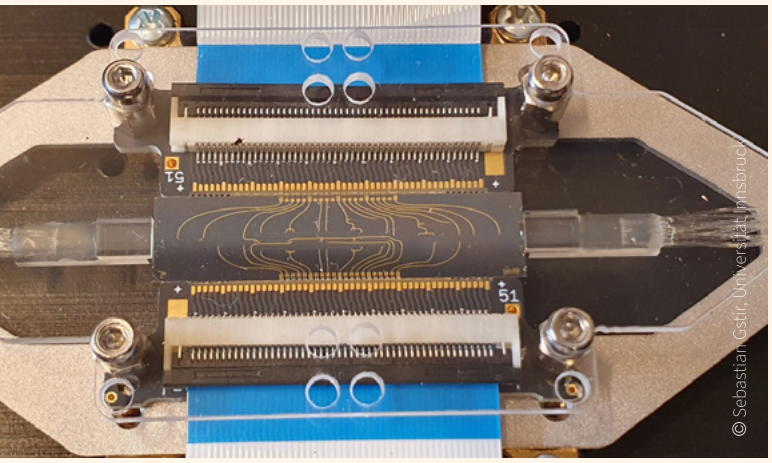


Figure 6: Example of photonic integrated circuit for optical quantum computing technology.

dependence. This is called the Heisenberg limit. Such a quantum sensor requires much fewer trials, particles, or averaging time than a conventional one. However, in practice it often turns out that producing the desired state also involves increased effort and therefore its benefit depends on the specific goal of the measurement. There are plenty of worthwhile applications, for example in the exploration of new raw material deposits, in seismology or in the detection of gravitational waves. In the latter experiments, quantum states are already being used today to make the kilometre-long interferometers even more sensitive.

In addition to the exploitation of quantum states, the field of quantum sensing also includes the use of individual quantum systems, such as a single atom, ion, photon and especially a single colour centre, for example as a sensor in a nanodiamond, which is then read out using quantum physical methods. An example of this can be found in the highlights above.

There are also other techniques, which, in a broad sense, belong to the field of quantum sensing. These include ***quantum imaging,*** where entangled states of light can be used to image objects with otherwise unattainable resolution, as well as quantum illumination. It is sometimes called quantum radar and objects can be located without the positioning system itself being detectable. In other words, undetectable radar. ●

Source:

[1] J. I. Cirac, and P. Zoller, Quantum computations with cold trapped ions, Phys. Rev. Lett. 74, 4091 (1995). | [2] I. Pogorelov, T. Feldker, C. D. Marciniak, L. Postler, G. Jacob, et al., Compact Ion-Trap Quantum Computing Demonstrator, PRX Quantum 2, 020343 (2021), https://doi.org/10.1103/PRXQuantum.2.020343. | [3] Scalable spin–photon entanglement by time-to-polarization conversion, npj Quantum Information (nature.com) | [4] Photoelectrical imaging and coherent spin-state readout of single nitrogen-vacancy centers in diamond | Science (sciencemag.org) | [5] H.-J. Briegel, W. Dür, J. I. Cirac, and P. Zoller, Quantum Repeaters: The Role of Imperfect Local Operations in Quantum Communication, Phys. Rev. Lett. 81, 5932 (1998), https://doi.org/10.1103/PhysRevLett.81.5932. | [6] F. Arute, K. Arya, R. Babbush, D. Bacon, J. C. Bardin, et al., Quantum supremacy using a programmable superconducting processor, Nature 574, 505 (2019), https://doi.org/10.1038/s41586-019-1666-5. | [7] H.-S. Zhong, H. Wang, Y.-H. Deng, M.-C. Chen, L.-C. Peng, et al., Quantum computational advantage using photons, Science 370, 1460 (2020), https://doi.org/10.1126/science.abe8770.



Figure 1: Students are introduced to the topic of optical data transmission at a workshop at the Vorarlberg University of Applied Sciences.

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Education, Training and Basic Research

Technological progress as a central aspect of our social development is based on the knowledge, expertise and motivation of well-educated people. Lifelong ***education*** is a basic prerequisite for the long-term development of photonic technologies and must therefore begin at a young age and occupy a correspondingly prominent position in any development scenario. In addition, rapid technological development makes it necessary to secure knowledge and expertise in the long term through continuing education and training measures like appropriate ***(in-service) training.***

In Austria, photonics is anchored in the curriculum in the university bachelor's and master's degree programs in physics and electrical engineering. The corresponding content is taught at the Vienna and Graz Universities of Technology and the Universities of Vienna, Graz, Linz, Innsbruck and Salzburg (teaching degree). At Vienna University of Technology, the Master's program in Microelectronics and Photonics has existed since 2013, with about ten graduates per year. As part of the specialization in the master's or dissertation program, the theses can be written on practically all current photonics research areas. At Vorarlberg University of Applied Sience, optics and photonics are part of the curriculum and cover the topics of lasers and materials processing, optical sensors and data transmission and applications in medicine. Project and master's theses are regularly carried out and successfully completed and dissertation students are supervised. The same applies to the University of Applied Sciences Technikum Vienna with its focus on IT security, medical engineering and optoelectronics and several optical training laboratories, including quantum cryptography and optical biophysics.

In order to meet current social challenges and develop innovative, sustainable scientific and technological solutions, we need excellently trained and motivated young people and appropriate framework conditions. ***Basic research***, as a prerequisite for any technological

innovation, plays a central role in this. Accordingly, research and its development scenarios within the framework of the respective thematic priorities occupy a large space in this roadmap. The following is thus limited to the general aspects and the requirements common to all areas.

Basic photonic research in Austria includes focal areas such as short-pulse lasers, quantum optics and communications, optoelectronics, micro- and nano-photonics. In addition, diverse spectroscopic methods, photonic measurement concepts, detectors and sensors, integrated optics, silicon photonics, photonic crystals, laser materials processing, optical communications, and light and illumination technologies are prominently represented. In many of these areas, research is being conducted at the top international level. However, virtually all research fields face the challenge of rising costs for experimental and technical infrastructure.

National Highlights

Education and youth work - the Photonics Explorer

The Photonics Explorer offers schoolchildren of all ages a comprehensive collection of exciting and instructive experiments to learn about the basic principles of photonics through exploratory learning. On the one hand, the Photonics Explorer includes documents for educational staff, who can use it to integrate experiments into their lessons with little effort. On the other hand, it contains ten copies of all the technical components needed to carry out experiments on topics such as colours, lenses, diffraction or polarization.

The material is designed for class sizes of up to 30 students in groups of three. An integral part of the Photonics Explorer concept is also a preliminary instruction for teachers, which takes place at the pedagogical universities in advanced training courses. Photonics Austria is the contact for obtaining Photonics Explorer and organizing the training courses.

Within the framework of the funded project "Phorsch! - Photonics for Schools "[1], photonics as a key technology of the 21st century is made comprehensible with the Photonics Explorer. Short video clips have already been created for the individual experiments in order to motivate students to experiment independently, to break down barriers and to provide teachers with background information on the experiments.

Basic research - special research areas

Young scientists are trained in photonics at Austrian universities at an international level. As part of their final theses, master's and doctoral students make a strong contribution to the progress of basic research, especially in network projects.

For example, new photonic devices in the infrared wavelength range have been developed in the “Österreichischer Fond zur Förderung wissenschaftlicher Forschung” (FWF) ***special research area*** IR-ON. Many chemical compounds (medicines, explosives, drugs, environmental toxins) can be clearly and quickly identified by their behaviour in the infrared spectral range. This research program was carried out by leading Austrian semiconductor and nanotechnology groups at the Vienna University of Technology, the University of Linz and by simulation groups at the University of Vienna and the Technical University of Munich.

Novel efficient and nanometre-scale tailored photon sources were researched and developed in the FWF special research area NextLite. Experimental and theoretical groups in Vienna, Graz, Innsbruck and Vienna have thereby bundled their research interests to implement completely novel concepts.

In Focus

Education & training

University studies at the bachelor's level teach the fundamentals of optics and photonics, where the contents generally do not require updating. However, the teaching contents of the following ***master studies*** are very much affected by the disruptive developments and rapid technological progress in photonics and thus deserve increased attention regarding their adaptation. This concerns both photonic core topics whose current developments lie, for example, in quantum, ultrafast or nano-optics, as well as areas that will increasingly find their

GREEN PHOTONICS ASPEKT

Basic research develops those concepts which, when implemented in the technological fields of photonics, lead to applications with greater efficiency, lower resource consumption and fewer emissions – which make green photonics possible in the first place. A new generation of excellently trained scientists is paying increased attention to environmentally friendly and sustainable developments.



way into photonics, such as IT and AI. On the one hand, such adaptations should not take place selectively but in a coordinated manner between the educational institutions in the federal territory. On the other hand, a long-term monitoring program is desirable. Both could be ensured by a committee of representatives from the educational institutions.

Based on the experience of the ***microelectronics and photonics program*** at the Vienna University of Technology, the need and possibility for further master studies with a focus on photonic topics should be evaluated regularly. For this purpose, the relevant international experience can be drawn upon, as master studies in photonics have been established at some European universities with a correspondingly high number of students, for example in Jena, Karlsruhe, Münster or at Imperial College London. A particularly interesting approach is taken by the ***EuroPhotonics*** Master's program, which is run jointly by universities in Marseille, Karlsruhe, Barcelona, Tampere and Vilnius. This teaches the pan-European aspect of photonics R&D starting at the undergraduate level and promotes broad technical training, mobility, but also networking of future photonics specialists.

A long-term goal must also be to increase the number of students. In order to make photonics "cool" in a gender-neutral way, expanded new approaches are needed in teaching photonics topics in ***school education*** at all ages. For example, ***Photonics Explorer*** is a proven teaching tool, which can be expanded nationwide and is used by students, accompanied by teacher training programs including freely available instructional videos. On the one hand, this also applies to proven formats that convey photonic content in a playful and age-appropriate way, such as children's universities or special offers at events like the Long Night of Research (e.g. Vorarlberg University of Applied Sciences[2]). On the other hand, more and more individual school partnerships have been established recently, such as the cooperation of the University of Applied Sciences Technikum Vienna with the Hertha Firnberg Schools or newly developed participative hands-on formats of the University of Applied Sciences Technikum Vienna[3] within the framework of the Knowledge Transfer Centre East and corresponding programs at the Vorarlberg University of Applied Sience.[4]

The opportunities after graduation, keyword lifelong learning, can and should be systematically expanded. ***Part-time university courses*** with a focus on photonics, which are, by nature, based on the demand from business and industry, have already been established in some areas. In any case, there should be information and further education offers for the transition to professional life.



Figure 2: Light guidance by total reflection and light decoupling at the end of an optical fibre.

New concepts must be developed and evaluated, as is the goal of the EU project CARLA (The European Photonics Career Launch Path[5]), which is currently running (2020-2022).

Such initiatives address the increasing demand for new workers in the photonics sector. A key aspect of this must be to increase the ***diversity aspects*** of education. Photonics workers have traditionally been recruited from technical fields of study such as physics, mathematics and engineering – in many cases heavily male-dominated studies. However, many other studies such as biology or life sciences also teach necessary fundamentals for photonics. For this reason, initiatives are also being carried out in Austria – including by CARLA – to make photonics known in these broader fields of study as well. Through established strategies such as publicizing female role models, social media campaigns on diversity, and inclusive events such as the CARLA camps, the openness of the photonics sector should be communicated so that its, currently still low, percentage of women is significantly increased and diversity in the sector is generally increased as well.

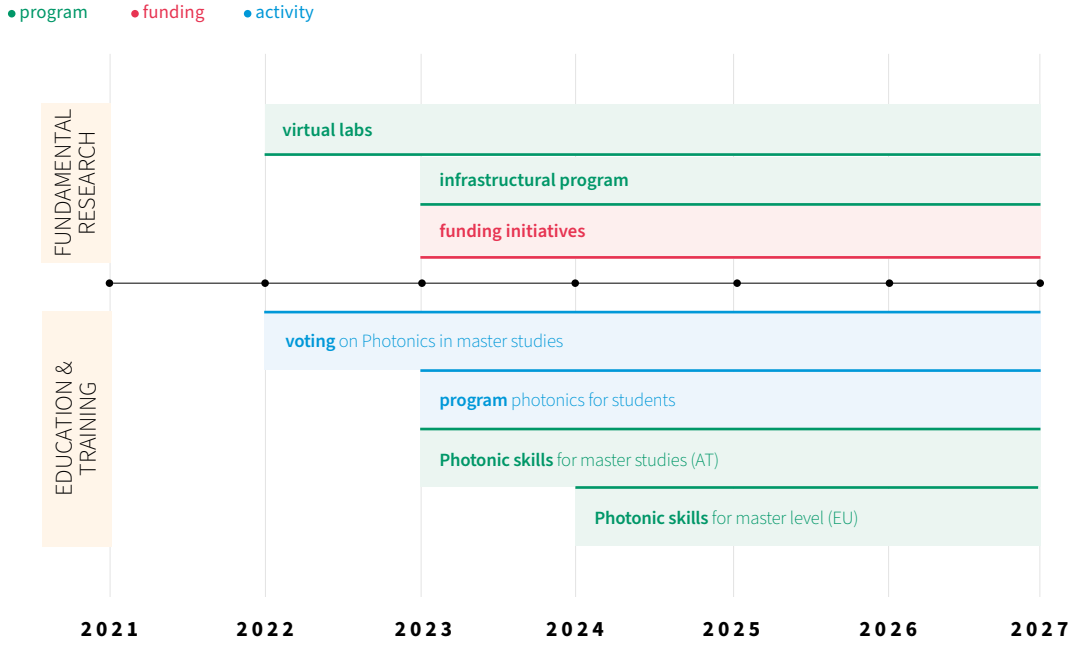
In general, initiatives are desirable that regularly (e.g. on the ***International Day of Light***, May 16) and permanently anchor photonics in public awareness. Of course, this point also includes persuasion work on all political levels. There are obvious starting points, since the use of photonic technologies in many cases – digital innovation, automated manufacturing, medical technology etc. – can easily be communicated as innovative, efficient and environmentally friendly. Such initiatives should by no means be limited to technological and scientific circles as the potential for application in the social and cultural sciences and also in the arts is at least as high.

Basic research

The rapid development of a large number of implementations of photonic technologies highlights the central role of research and innovation, as can be seen from the discussion of the application-specific sections in this roadmap. In addition to application-oriented research, however, societal innovation can only be sustained through ***basic research*** without any immediate application purpose. This is backed up by the fact that its sustained positive effects on general economic development are also known and documented.[6,7] In the field of photonics in particular, there is a long list of examples of how results from basic research projects have been transferred to applications in a short time: Worth mentioning here are ultra-short pulse lasers and the Nobel Prizes for Physics in 2009 (CCD chips), 2014 (blue LED) or 2018 (femtosecond technology, optical traps) illustrate this fact.

Basic photonic research requires cost-intensive infrastructure, such as equipment for micro- and nanofabrication, microscopy and spectroscopy systems, laser systems with ultrashort pulses and high intensities, quantum optical systems etc. However, for research institutions, the acquisition or renewal of this infrastructure is always linked to financial imponderables, which makes long-term and sustainable planning difficult. Particularly in a highly dynamic and rapidly growing field such as photonics, it is necessary to ensure the international competitiveness of national basic research through appropriate infrastructure funding. In this context, a large synergy potential can be exploited through joint acquisitions and operation by several research institutions, which is why prioritization of future acquisitions is advisable for cooperative use. This also includes accompanying measures for efficient networking, whereby appropriate approaches, such as the research infrastructure database of the Federal Ministry Republic of Austria - Education, Science and Research (BMBWF), can be used. Research institutions with complementary infrastructure could join forces to form ***virtual laboratories*** and subsequently coordinate further investments. Other research areas that will play an important role for photonic technologies in the future (e.g. computer sciences/AI) or research areas that are relevant to the thematic focus of this roadmap from an interdisciplinary perspective should also be included in the planning in order to establish networked labo-

TIMELINE



ratory infrastructures and strengthen interdisciplinary research approaches in a holistic view. Of course, the joint use of research infrastructure and coordinated research programs under one roof can and should also be pursued, with the ***Graz Centre of Physics*** (planned reference 2030) being the most recent example.

Photonics is closely linked to other fields of research and development (microelectronics, novel materials, life sciences, micro- and nanofabrication, AI, robotics etc.) and creates completely new opportunities and perspectives through mutual synergies. The thematic environment in the development of the research infrastructure must also be accordingly broad.

The growing need for research in the field of photonics, in line with the technical and environmental requirements, must be reflected in the priorities of national funding programs. This will require an appropriate effort to convince the decision-makers.

In the context of international research funding, the increased use of European programs is obvious. In addition to specific thematic calls for proposals, the possibilities of the Field Effect Transistor Quantum Flagship should be exploited, as well as funds from the ERC pro-



Figure 3: At the Children's University of the Vorarlberg University of Applied Sciences, children show keen interest in the excitingly presented topic of lasers and participate energetically.

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Figure 4: Children use flashlights to learn how communication is possible through light.

gram, following the European Research Council (ERC) Starting Grant to Bernhard Schenk, AIT.

Summary

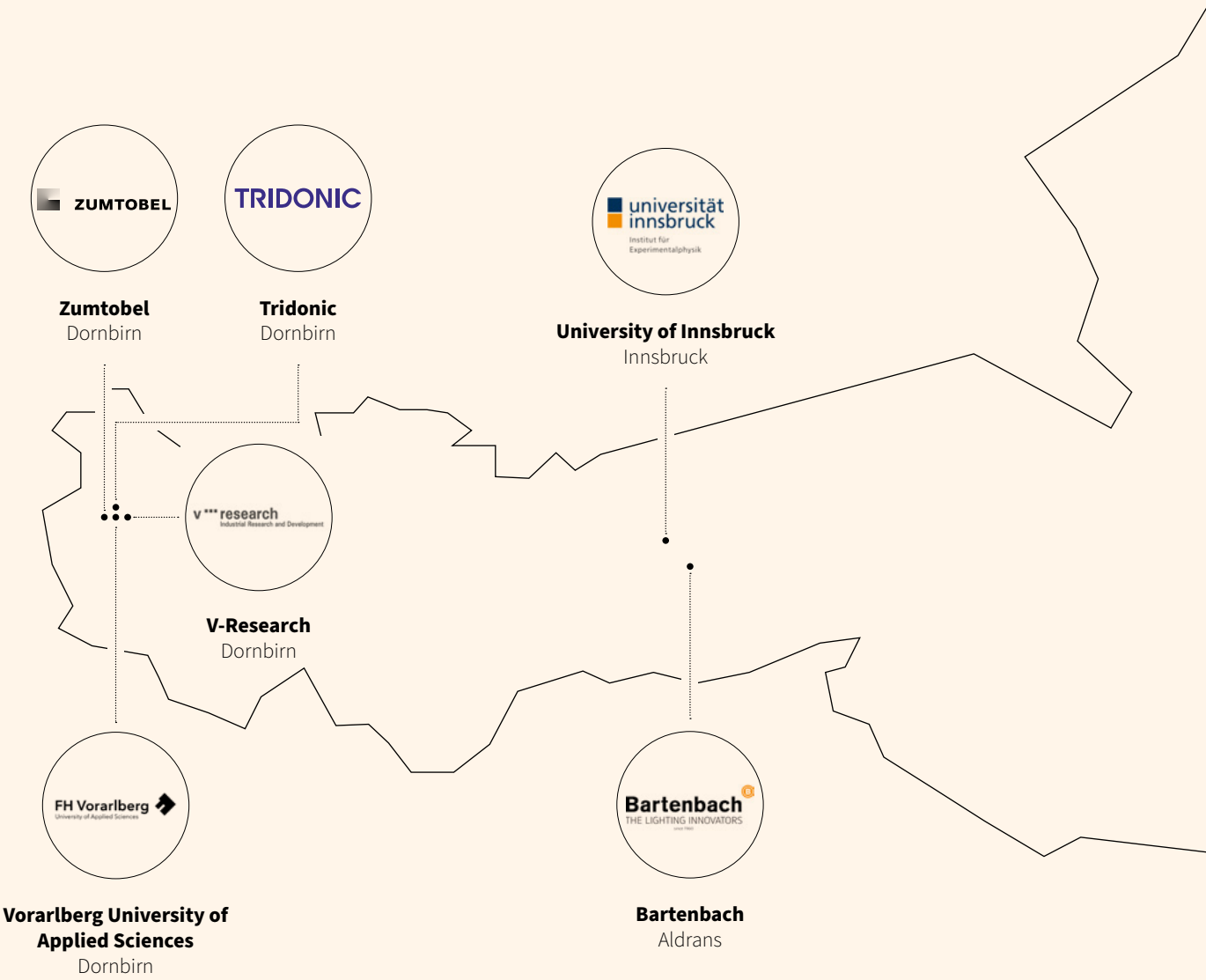
Austria's education and research activities in the field of photonics are at a high level compared to other countries. However, additional efforts and measures are required to maintain this level. In the school environment, it must be possible to get even more young people interested in the subject, for example by presenting photonics in a gender-neutral "cool" way. Research is confronted with rising infrastructure costs. Sharing cost-intensive infrastructure is one way to address this problem. Together with the challenges of the increasing interdisciplinarity of photonics research topics, this aspect requires new approaches in organization and cooperation on a nationwide level, as is already being realized to some extent through the establishment of the Graz Centre of Physics. ●

Source:

[1] Phorsch! – PHOTONICS für Schulen, https://projekte.ffg.at/projekt/3761898 (abgerufen 20.5.2021). | [2] D. Seyringer, C. Burtscher, G. Piredda, A. Prasad and J. Zehetner, The Night of Science: Optics and Photonics for All, The European Conference on Technology in the Classroom 2016 (ECTC2016). | [3] Wissenstransferzentrum Ost – KV MINT, https://www.wtz-ost.at/schwerpunkte/mint/ (abgerufen 20.5.2021). | [4] D. Seyringer, Children's University: Optics and Photonics for Children, Journal of International Scientific Publications - Educational Alternatives, 13, 130 (2015). | [5] The European Photonics Career Launch Path, H2020 ICT-05-2019, 2020-2022. | [6] A. J. Salter, B. J. Martin, The economic benefits of publicly funded basic research: a critical review, Research Policy 30, 509 (2001). | [7] M. Dalziel, J. Roswell, T. Tahmina, X. Zhao, Impact of government investments in research and innovation: a review of academic investigations, Optimum Online: The Journal of Public Sector Management, 42, 19 (2012).

Partner-Institutions

The organizations presented have made significant contributions to this roadmap, but represent only a small part of the broad Austrian photonics community. Further input was gathered from the members of Photonics Austria as well as from numerous other Austrian institutions.



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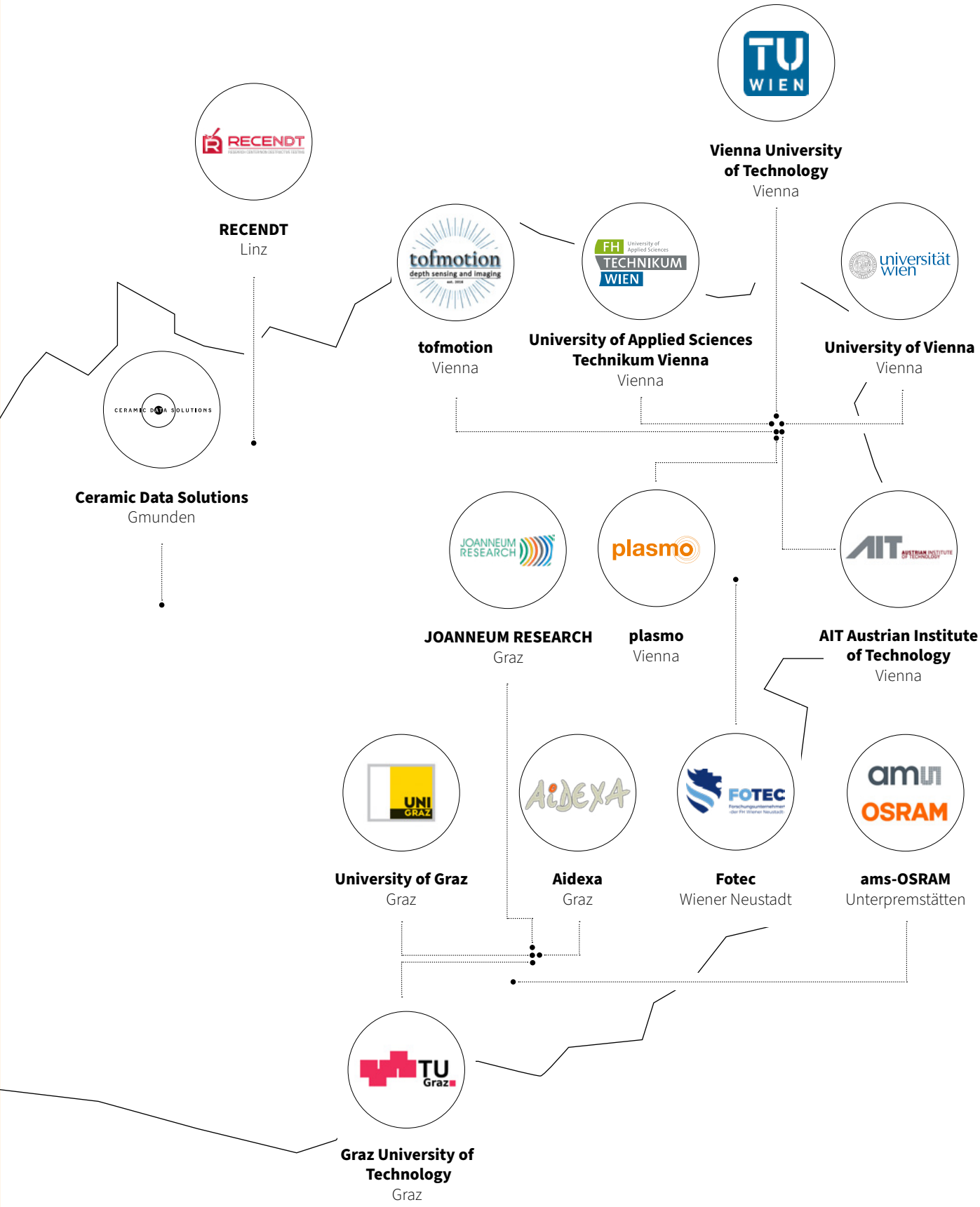
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Long Term Vision

ALFRED FELDER
CHAIRMAN OF THE BOARD &
CEO ZUMTOBEL GROUP

Photonics has been identified by the European Commission as ***one of the most important key technologies for the 21st century***. Thanks to the fibre optic network, for example, it was possible during the Corona crisis to switch to home offices on a large scale, to hold meetings, lectures and school lessons online and even to monitor and control many machines from home.

Just as miniaturization and the integration of discrete components once led to the triumph of microelectronics in the semiconductor sector, enabling everyone to carry a thousand times more computing power in their smartphones at all times, than was available for the first moon landing – photonics today makes it possible to integrate complex devices into small, mobile units that process data at the speed of light. In the field of ophthalmic diagnostics, for example, this has enabled expensive table-sized devices to be scaled down to more affordable portable units that can now be easily used in the field. Similarly, photonics already enables the precise detection of various diseases, which is of inestimable importance, especially with regard to pandemics.

Even though photonics already strongly shapes our daily lives and ***neither smart homes nor streaming services or social media would be possible without photonics***, its importance will increase very much in the future. Due to the high population growth, there will soon no longer be enough land for food production, which will lead to the need to switch to vertical farming and food will have to be produced in ***high-rise buildings with artificial light***. This will eliminate long transportation distances for food and, ideally, the fruits and vegetables in the supermarket will only need to be transported down to the sales area from the upper floors, where they are grown. By providing optimized light spectra during growth, it will even be possible to increase the vitamin content and flavouring in fruits and eliminate the need for artificial fertilizers and insecticides, benefiting our environment.

Light will be able to do much more. One of the great challenges of our time is to stop climate change and reduce CO_2 emissions. Replacing old lighting equipment with new LED lighting systems in all areas will not only save a massive amount of money, because operating costs are much lower, but will also save a massive amount of CO_2 and thus ***make an active contribution to the environment*** (in a city like Vienna, the reduction in the public sector would already amount to over 40,000 tons of CO_2 per year). However, at home and at work the new lighting systems will do much more: they will use activating light to help us get up in the morning, they can strengthen our immune system, promote concentration, reduce the risk of certain types of cancer and other diseases, reduce sleep disorders or help to synchronize the day-night cycle.

Light is our future – let us use it together to improve our lives and do something for our environment. ●



Executive Summary

The Photonics Austria Roadmap provides an overview of the multi-layered Austrian photonics landscape, its status, orientation and future research needs. Austria has numerous companies of international stature that are among the market leaders and pioneers in their sectors. In addition, numerous university and non-university research institutions as well as SMEs are involved in photonics and make an invaluable contribution to innovation in the topics described. Photonic technologies offer solutions to the major challenges facing our society, first and foremost the European Green Deal, with a savings potential of 3 billion tonnes of CO2 per year. [1]

In ***sensor technology and metrology***, future topics range from the development of components to systems and applications, process integration and data evaluation to certification. Key technologies such as time-of-flight, structured light, active stereo vision and their further developments will be important in augmented reality applications in the future, and chemical imaging (hyper-spectral imaging) provides information about the spatially resolved chemical properties of products. Although other factors such as robustness are often of great importance in industrial applications, there is an increasing overlap with the consumer sector, such as the use of multispectral sensor technology to control display brightness. In addition to miniaturisation with improved sensor properties, optimisation of speed and price are further central development topics for the coming years.

Austrian players in ***production and quality assurance*** are researching and offering outstanding solutions in many areas. These include, for example, multiphysical numerical simulations of laser machining processes, in-line monitoring of laser-based manufacturing processes or laser processing and ultraviolet microstructuring for the production of functionalised surfaces (riblets) to reduce flow resistance. Photolithography, novel optical coating methods and photonic materials as key elements of numerous applications are also the focus of research and development in the coming years. Since the resources required for research and development are considerable, better networking, both between research institutions and companies as well as amongst research institutions themselves, is being sought to bring about a further boost in innovation.

Domestic research and development activities play an extraordinary role in photonics for ***life science, health, agriculture and the environment***. In the coming years, photonics will make a significant contribution to the further development of the healthcare system through its use in medical research, prevention, diagnosis and treatment methods. In environmental protection, photonic methods are used to continuously measure fine dust particles and pollutants from the air and provide the information in real time. The same applies to water quality monitoring, water pollution control and wastewater disposal. In agriculture and forestry, hyperspectral imaging technology can record areas with high spatial resolution to register forest fires and assess damage.
It helps to provide data for predictive models or to increase yields while at the same time reducing the use of fertilisers, pesticides and herbicides. Further development of these technologies and applications as well as data processing are primary goals.

Information systems and communications technology have long been determined by photonics.
Austrian companies and research institutions contribute significantly to this, for example by researching and developing photonic integrated circuits such as monolithic integrated silicon optoelectronics or durable data storage based on ceramic coatings on sapphire glass wafers. In optical data communication, the great challenge is to further increase performance and energy efficiency simultaneously. Due to their advantages over microelectromechanical systems, photonic integrated circuits are not only interesting for 6G applications. The major goal is to realise freely programmable photonic integrated circuits. Their currently still low integration density is seeing a steady increase in performance similar to Moore's law.

Light is not only for seeing (visual), but also has a great influence on our mood, well-being and health (non-visual). Adequate ***lighting for Smart Urban and Rural Solutions*** will therefore increase in importance in the future. Cornerstones of Human Centric Lighting are sensors and intelligent, Internet-of-Things-enabled LED drivers. There is a need to develop not only optimised, sustainable, efficient and cost-effective drivers, but also new optics. Free-form optics, nanostructures on optical surfaces, new materials and numerous other technologies need to be researched in order to open up new applications in Smart Lighting and, at the same time, to further the greening of the technology. Digital engineering methods such as the "digital twin" and new, improved simulation methods and systems are of the greatest interest. More intensive research is needed to increase the importance of light in society with Human Centric Light, Smart Lighting and Horticultural Lighting.

Connected mobility, transport and safety are exciting future topics with very different aspects - also for photonics. Well-known, realised examples are matrix LED headlights and laser diode-based high beam technology. Equipping Unmanned Aerial Vehicles, drones with LiDAR, optical directional radio through Free Space Optics or chemical, biological, radioactive, nuclear or explosive sensors allows emergency forces to safely analyse unknown terrain - thanks to Austrian research also in real time in the future. Autonomous Driver Assistance Systems lay the foundation for future fully automated driving. Frequency Modulated Continuous Wave Light Detection and Ranging, flash-/LiDAR, Time-of-Flight and their evolution play a key role in this. For the first time, fibre-optic Distributed Acoustic Sensing enables seamless condition, traffic and safety monitoring with a single, already laid fibre-optic cable. To develop all this and make it a reality requires further efforts, but also early cooperation between innovation drivers and standardisation institutes.

Since the early 1990s, Austria has been a leader in fundamental quantum research, which is the basis of modern informations technologies. Today, the first quantum computers "Made in Austria" are ready for series production. Future research and development in ***photonic quantum technology*** will focus on quantum communication, quantum computers and quantum sensors. For example, in order to establish security-relevant quantum key transmission on a broad scale, the aim is to miniaturise the electro-optical elements. For photonic quantum computers, in order to keep up with international competition, research is required in numerous key technologies, such as precise lasers or low-loss waveguide technologies in integrated circuits. A major benefit of quantum sensor technology is, among other things, the increase in measurement accuracy and the sensitivity of the measuring instruments. But here, too, a lot of theoretical and practical research work is still needed.

Austrian ***education, training and fundamental research*** in photonics is at a high level in international comparison. Key elements in youth work are the Photonics Explorer and projects such as "Phorsch! - Photonics for Schools". On this basis, photonics must be taught in an inclusive way to increase the number of students. As a result, the curricula of the master's programmes must be continuously reviewed and adapted in line with the rapid technological progress of photonics and supplemented by part-time university courses with a photonics focus. However, societal innovation also requires fundamental research without an immediate application purpose, all the more so since its sustainable positive effects on general economic development are also known and documented. However, research is confronted with rising infrastructure costs. Only joint use of cost-intensive infrastructure and new approaches to organisation and cooperation on a nationwide level could alleviate this problem.

The innovative, internationally recognised Austrian photonics community is a leader in many areas. However, in order to maintain this position, or even better, to expand it, great joint efforts are required. Cooperation, coordinated research plans and organisational and financial support are required. This does not concern only a single topic, but all topics equally. ●

Source:

[1] Spectaris, „LICHT als Schlüssel zur globalen Nachhaltigkeit“, 2019

Abkürzungsverzeichnis

ADAS	Autonome Driver Assistance System
ASIC	Application-Specific Integrated Circuit
BD	Big Data
BMBWF	Austrian Federal Ministry of Education, Science and Research
CARLA	The European Photonics Career Launch Path
CBRNE	chemical, biological, radioactive, nuclear or explosive
CCD	Charged-Coupled Device
CMOS	Complementary Metal Oxide Semiconductor
CT	Computed tomography
CV-QKD	Continuous-Variable QKD
cw	continuous wave
DALI	Digital Addressable Lighting Interface
DVD	Digital Versatile Disc
EEA	European Environment Agency
EEL	Edge-Emitting Laser
ERC	European Research Council
R&D	research and development
FFG	Austrian Research Promotion Agency
FMCW LiDAR	Frequency Modulated Continuous Wave LiDAR
FMLA	Freeform Micro-Lens Array
FPGA	Field Programmable Gate Array
fs	femtoseconds
FSO	Free Space Optics
FTIR	Fourier-Transform Infrared Spectroscopy
FWF	Austrian Science Fund
GaN HEMT	Gallium Nitride High Electron Mobility Transistor
HCL	Human Centric Lighting
HDD	Hard Disk Drive
HPC	High Performance Computing
ICT	Information and Communication Technologies
IoT	Internet of Things
IR-ON	InfraRed Optical Nanostructures
KET	Key-Enabling Technology
AI	Artificial Intelligence
SME	Small and Medium-sized Enterprises
LED	Light-Emitting Diode
LIBS	Laser-Induced Breakdown-Spectroscopy
LiDAR	Light Detection and Ranging / Light Imaging, Detection and Ranging
LiFi	Light Fidelity
M2M	Machine-to-Machine
MEMS	Microelectromechanical Systems
MIR	mid-infrared
ML	Machine Learning
MMI	Multimode Interference Coupler

NDT	Non-Destructive Testing
NGOA	Next Generation Of Access
NIR	near-infrared
NRATF	Network Resilience Aware Topology Formation
OCT	Optical Coherence Tomography
OLED	Organic Light Emitting Diode
ÖPNV	local public transport
PAT	Process Analytical Technologies
PC	Photonic Crystal
PCB	Printed Circuit Board
PDK	Photonic Design Kit
PIC	Photonic Integrated Circuits
PMMA	Poly(methyl methacrylate)
PSSP	Photonic Sensing for Smarter Processes
QKD	Quantum Key Distribution
QRNG	Quantum Random Number Generator
R2P	Role2Plate
R2R	Role2Role
SSD	Solid State Drive
THz	Terahertz
ToF	Time-of-Flight
UAV	Unmanned Aerial Vehicle (drone)
UV-C	Ultraviolet radiation in the range C between 100 and 280 nm
VCSEL	Vertical-Cavity Surface-Emitting Laser
VOC	Volatile Optical Compound
WDM	Wavelength Division Multiplexing
XCT	X-ray Computed Tomography
YAG	Yttrium Aluminium Garnet



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