Photonics Roadmap

PhotonicsNL
NETHERLANDS

PhotonDelta

NWO

Rijksdienst voor Ondernemend Nederland

HTSM Roadmap Photonics 2020-2023,
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By PhotonicsNL, Dutch Optics Centre,
PhotonDelta, NWO, RVO and partners.

Inhoud

0. Introduction

Since 2018 the Photonics Roadmap is based on the Societal Challenges as described by the Dutch Top Sectors. During the last 5 years there have been some important developments in the world and in the field of photonics in particular.

The photonics ecosystem in the Netherlands has evolved since the last Roadmap. Through cooperation at national level important steps forward have been made. This included among other activities:

1. The creation of the *The National Photonics Agenda,* a higher TRL level initiative for (Integrated-) photonics and optics and the further clustering of the optics community through PhotonicsNL, PhotonDelta and Optics Netherlands.
2. The recognition of photonics as a key enabling technology (KET), with multiple application areas and technologies, for example Quantum Technologies and Artificial Intelligence, has been achieved.
3. Increased interactions of the Dutch Photonics Ecosystem with international partners.
4. Most recently, the award of the National Groeifonds grant with a total budget of 1.1B€ for the years 2023-2029 for research, innovation and industrialization of the Dutch ecosystem for integrated photonics.

Photonics as a key- enabling technology is recognized and embedded in the *Kennis- en Innovatieagenda Sleuteltechnologieën 2020-2023*, 15 October 2019 and various *Meerjarenprogramma's* (MJP's) for example #21 Photonics for Society, #22 Integrated Photonics, #23 Light & Intelligent Lighting and #93 Photovoltaic Technology (Solliance) and crosslinked with the other Roadmaps in HTSM.

The extensive impact of (integrated-) photonics and optical technologies in the Netherlands is obviously present in the vast ecosystem of more than 300 companies that rely on optical technologies in their (primary) business processes.

Another important development is the increase of interest by the financial sector. PhotonDelta has leveraged this interest in several investment rounds, resulting in multiplications of the initial capital injections committed by PhotonDelta. As a result, there has been an increase in trust in the production promise of the front and back-end foundries which is also a major element of the growth fund program. In 2023 a new venture fund "photon ventures" was launched to further develop integrated photonics business.

Compared to the previous Roadmap this updated Roadmap will give a more extensive overview of the role of Photonics to help solve Societal Challenges. Addressed by the link with other technologies and applications. This Roadmap is especially focused on the Research Agenda for the Netherlands but we realize that the valorization of research to business is an essential aspect to tackle the societal challenges which get attention with valorization aspects. It is within the potential of the photonics ecosystem in the Netherlands to create unicorns, even more so, if we ensure, the entire value chain, from fundamental R&D all the way to large scale production and packaging is to be created in NL. In comparison to the previous version, this updated Roadmap offers a more comprehensive perspective on how Photonics plays a crucial role in addressing Societal Challenges. This is achieved by exploring its interconnections with other technologies and applications. While primarily concentrating on the

Research Agenda for the Netherlands, this Roadmap acknowledges that translating research into business ventures is a vital component in tackling the societal challenges that are being highlighted through valorization efforts.

Recognizing the potential of the photonics ecosystem in the Netherlands, there's an opportunity to foster the growth of groundbreaking companies, even more so if we ensure the entire value chain — spanning from foundational research and development to large-scale production - is established within the Netherlands.

1. Societal challenges and economic relevance

Photonics is the key enabling technology that uses the properties of light for a wide range of applications. The importance of photonics in supporting and enabling different services and products is increasing. As we aim to meet the demand for growing needs in the area of communication, living comfort and health our ambition is to do so while minimizing the environmental impact these technological developments have. The photonics ecosystem of the Netherlands encompasses more than 300 companies and institutions where thousands of people already work on photonics directly or indirectly, both at large companies as well as SMEs and start-ups in various sectors.

Within this document, we present the Photonics Roadmap, aiming to bring together individuals from academia, business, and government. Our roadmap is constructed upon the following foundational principles:

- Enhancing Excellence: The Netherlands holds an international lead in various photonics research domains. Preserving and, when feasible, augmenting this position is imperative. It's essential to also navigate the space between fundamental science and practical applications, preventing a potential hindrance to innovation.

- Significance in Addressing Societal Challenges: Photonics presently plays a significant role in resolving critical contemporary societal issues.

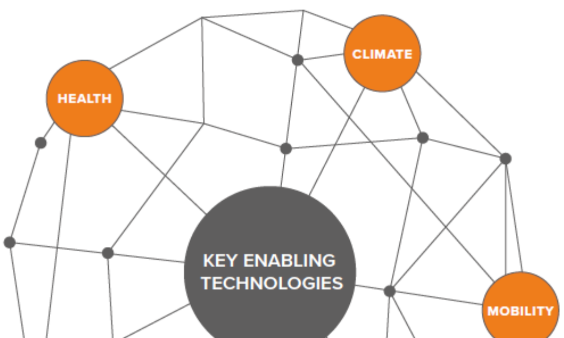
- Amplifying Research Yield: Our focus should encompass valorizing a substantial portion of scientific knowledge and infrastructure, aiming to maximize the returns from research efforts.

- Nurturing Human Capital: Cultivating a highly educated populace is pivotal in realizing our aspirations, whether directed towards pioneering research or the social and economic application of knowledge.

- Collaborative Endeavor Involving Science, Government, and Enterprises: The responsibility for driving this process lies jointly with the scientific community, government bodies, and corporate entities.

1.1 Societal challenges addressed in this roadmap (with examples)

Photonics is the physical science and the technology of light (photon/wave) generation, propagation, modulation, signal processing, switching, amplification, detection and sensing.



The Netherlands has a great history in the field of optics and photonics and to this day, the Dutch scientists and engineers are still pioneers in researching and developing new technology in the field of photonics.
As Key Enabling Technology (KET), photonics provides sustainable, energy-efficient, miniaturized and low-cost products that allow innovative solutions in a wide field of applications. As such, photonics contributes directly to solutions for the grand contemporary societal challenges.

1. Climate, including energy and water
   In order to reduce emission of greenhouse gasses, more energy efficient photonic solutions are being developed. This includes very efficient light sources, (O)LEDs,microLED, energy generation by highly efficient solar cells and more energy efficient data centers by application of photonic ICs. Innovative optical technologies are being developed that convert sunlight directly into hydrogen or syngases contributing to reduce the greenhouse gas effects. Photonics in climate change can also be used for advanced detection technologies, such as earth observation using advanced optical pollution detection instruments (such as TROPOMI) and water quality & air safety analysis.

2. Sustainability and Circularity
   Sustainability has become a new imperative in a world with a growing population and limited resources. Smart industry, precision agriculture, avoiding waste and a circular economy are all drivers for information driven systems. These require sensing and monitoring and smart processes and here Photonics can play a key role. Energy efficient data communication , remote sensors in precision agriculture and farming robots , efficient light sources, control systems in industry and environmental monitoring are all examples of key contributions Photonics can make.

3. Health
   To increase longevity and quality of life for an increasingly aging population the use of bio-photonic technologies and their implementation in new applications and services is of great interest. These include radical novel diagnostic approaches enabling early and reliable detection and prevention, new handheld or wearable (integrated) photonic diagnostic devices enabling point-of-care diagnostics, and monitoring of the evolution of diseases.

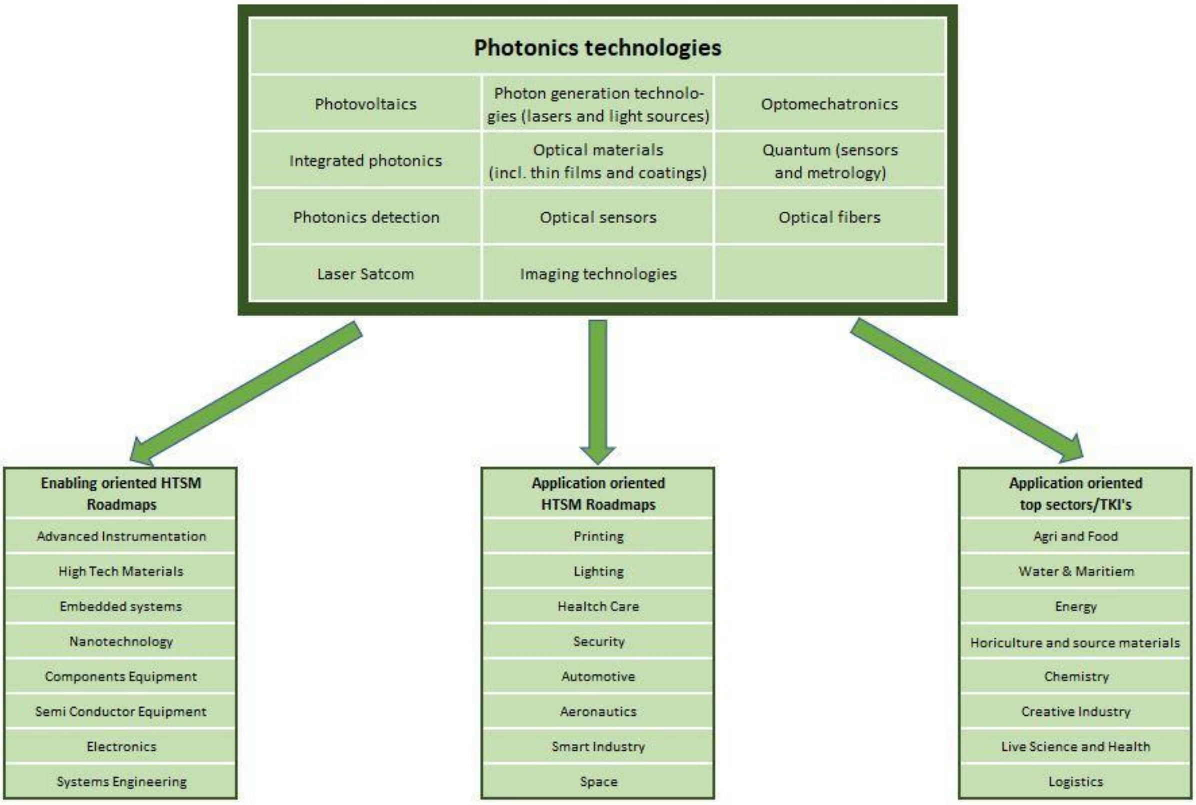
4. Safety and Security
   With photonic sensing and imaging technologies we can provide higher levels of security and safety. Sophisticated surveillance, authentication and encryption technologies are used in the communication field as well as in logistics. Examples are nano-dust detection, terahertz imaging technology and secure key and information exchange in a “quantum internet”.

5. Mobility
   Smart and green mobility needs the development of various technologies. Photonics plays an important role when it comes to autonomous mobility (e.g. LIDAR) and the abundance of sensory data being created by terrestrial and airborne platforms (including satellites) requires low-latency and multi Terabits/sec network capacities.

6. Communications

   Data consumption is growing exponentially on a global scale. This drives the need for ever faster switches and systems in data centers, doubling every 2 years. Moreover the energy consumption is becoming untenable both from a cooling point of view as from the overall energy consumption which is in the Netherlands already about 3% of electricity generation. The recent growth in AI applications is resulting in a further energy consumption. (Integrated) Photonics is the driver to deal with these challenges. In telecom you see comparable trends with mobile data use surging with 5G and 6G coming up in the next 5-10 years.

Photonics as key enabling technology in top sectors and roadmaps in the Netherlands



1.2 World-wide market for photonics, now and in 2030 (with examples)

According to a recent European Investment Bank (EIB) study the global Photonics market is truly enormous with a market size of €652Bln in 2019. Europe represents €103Bln of the total , where it should be understood that this market represents a wide variety of products from lenses to instruments, lithographic scanners, displays, PV etc. Not only is it very large, with 7% it also grows much faster than the average GDP.

During the next transition towards digitization, it is clear that photonics technologies are essential and with further development, we are taking steps towards realizing ‘Europe’s Age of Light’.

With about five thousand European photonics companies and organizations, Europe currently holds the second place in the world’s market, just behind the USA, and well ahead of China. The collective efforts of government, science and industry and the successful networking across Europe are an important part of this.

Photonics technologies are key enablers for future mega-markets such as Internet of Things (IoT), cybersecurity, quantum technologies, artificial intelligence, healthcare and additive manufacturing among others.

1.3 Competitive position of the NL ecosystem (market and know-how)

Photonics is a fast growing sector and therefore an important driver of employment and economic growth in the Netherlands.
Since the publication of the national agenda of photonics in 2018 the impact of photonics as key enabling technologies has been growing steadily. More than 300 companies with its Headquarter in the Netherlands contribute €30 Bln revenue to the economy with an annual expected job growth of 5-20 percent.
The high growth expectations are reflected in the initiatives taken at the regional level. Several provinces collaborate in order to build on their strength in the field of integrated photonics aiming for thousands of new jobs in the future, see CITC and PITC. The leverage photonics offers to the manufacturing industry and end markets is considerable.

1.4 Regional expertise

The expertise required for photonics in the Netherlands is not concentrated in one location. There are many different locations working on a variety of topics. Below some examples:

- The Amsterdam region has a wide palette of photonic activities. The medical centers, VU and several start-ups are strong in medical photonics with a focus on the development of affordable minimally invasive screening methods to be able to make diagnoses very quickly and reliably. ARCNL and AMOLF are increasingly investing in computational imaging and metrology, as well as building a strong activity in EUV light sources, directly relevant for ASML. AMOLF and UvA are leading in the development of next generation photovoltaics, leveraging photonics for light management. Finally in the national QuantumDelta initiative quantum nanophotonics and photonic technology for quantum information are important. These are important in Amsterdam at AMOLF (quantum nanophotonics) and UvA (IqClock).
- The Nijmegen area is working on further integration of microelectronics with photonic technology as well as the knowledge for the large-scale packaging and testing of such chips ('back-end'). The strong supply chain of electronics is empowered through new initiatives, such as CITC to foster growth of the photonics industry.
- The Twente region, with the University of Twente and the MESA+ Nanolab, has a strong knowledge base with respect to the development and production of nanophotonics, in particular silicon nitride integrated photonics, integrated lasers, microwave photonics, 3D nanophotonics, photovoltaics and scattering optics. Further activities focus on optical quantum information technologies within the Quant center, optical sensing and medical diagnostics; opto-mechatronic systems; generic packaging technology, integration with microfluidics and the assembly of photonics and electronic circuits. The University of Twente is actively supporting start-up's through direct participation by supplying capital, IP and facility sharing with innovative start-up's such as PHIX for assembly and packaging of integrated photonics and QuiX Quantum for commercializing photonic based quantum technologies. As part of the PhotonDelta growth fund large investments in R&D as well as an upgrade of the MESA+ facilities and a dedicated foundry (New Origins) are planned.
- The North Brabant region has various photonics-based activities. They have a strong position in integrated photonic chips based on Indium Phosphide, in related materials and in communication systems. The region also builds actively on the developments needed for production and the back-end processes to bring these technologies to the market. Equipment manufacturing, including the required photonics technologies, is also strong in this region, for photovoltaic, microelectronics and healthcare applications. Photonic technologies for consumer electronics and lighting are also developed by many organizations. ASML is an innovation leader in semiconductor manufacturing equipment. ASML develops lithographic scanners (with extreme

ultraviolet (EUV) and deep ultraviolet (DUV) light), metrology and computational lithography tools with partners from industry and academia throughout the Netherlands (TNO, ARCNL, TU Eindhoven, TU Delft, University of Twente). Also here as part of the PhotonDelta Growth fund large investments in R&D, startups and InP industrialization are being planned.
- In 2022 PITC started as an integrated photonics development center. It is a cooperation between TNO, and the universities of Twente and Eindhoven and active in both regions
- The South Holland region has a strong position in opto-mechatronic and optical systems for applications in industry and space, and in imaging techniques leading to the development of precision instruments and analysis techniques. There are also development activities for the emerging field of quantum optics.
- In the North of the Netherlands there are strong activities in material development for light detection and photovoltaics.

For successful positioning within European and worldwide markets we present the Netherlands as a single, coherent, and well-synchronized photonics region. However, while the Dutch photonics ecosystem has these strengths, global competition remains intense. Other countries and regions also have vibrant photonics ecosystems and are investing in research, development, and commercialization. Staying competitive requires continuous innovation, investment, and adaptation to emerging trends by collaborations, network meetings and events, specifically for collaborations.

2. Applications and technologies

Photonics is one of the key technologies for the 21st century enabling solutions for many of the global societal challenges. History shows that scientific and technological breakthroughs lead to new and revolutionary industrial activities and continue in the decades after the invention. The 21st century has been named the century of the photon. With our knowledge and technological breakthroughs we are ready to profit from this: achieving a new level in the generation, control and the application of light in many high tech markets where Dutch industry and knowledge institutes are playing a prominent role.

2.1 State of the art review and outlook for industry and science

Photonics refers to a broad, diverse and synergetic scientific domain. It includes freespace imaging and non-imaging systems, fiber optics for communication, integrated optics, microscopy, biomedical optics, laser technology, nonlinear optics, remote sensing, metrology, spectroscopy, nano photonics, plasmonics, metamaterials, quantum optics and quantum communication.

Dutch academic research is at the forefront of many of these disciplines. It has a strong track record in transferring innovations to the Dutch industry. Photonics is an enabling technology for a range of applications. Access to photonics expertise and experts strengthens the competitive position of Dutch industry in several Top sectors and Roadmaps within the HTSM top sector. For successful applications, a system engineering approach is needed. Apart from deep expertise in a discipline (like optical design), it is also necessary to understand and appreciate other disciplines (like integration, manufacturability or computational imaging). A network of institutes and industries and communication between them is therefore essential.

Photonic technologies and applications are developing rapidly in the Netherlands. This section reviews these developments. Some recent achievements of universities and research institutes are highlighted in the text boxes.

• **New materials, methods and processes:** One of the pillars of new optical technologies are innovations in material science and ways to analyze, engineer and process a broad range of materials. These materials include glasses, semiconductors, plasmonic materials, metamaterials, gradient index materials, photonic crystals, nano- (plasmonic) structures, quantum dots, nano-crystals, 2D materials, nonlinear materials, doped materials, magneto optical, electro optical and random materials, organic materials, organic-inorganic combinations and new bio materials.

Innovations in materials and their processing enable photonic devices with improved efficiency and flexibility, in extreme environmental conditions, and in combination with other key enabling technologies such as microelectronics. New methods, processes and equipment for optics manufacturing are being explored. This includes injection molding, diamond turning, magneto-rheological finishing, 3D printing, and robot polishing.

• **Freeform and micro optics:** Freeform components offer a large number of parameters for image quality optimization in a single optical surface. This enables developing more compact optical instruments with fewer components. Applications include remote solid state lighting, photovoltaics, microscopy, advanced spectroscopy, health instruments, remote sensing systems and lithography. 3D printing of high quality micro-optical components enables application of ultra-compact optical systems.

• **Adaptive optics:** optical components that can dynamically shape the wavefront of light, can be used for astronomy (correcting atmospheric turbulence), industrial applications (compensation for thermal deformation) and biomedical applications. A growing market for adaptive optics is in optical satellite communications. Spatial light modulators are used to create wavefronts with programmable intensity and phase distribution.

• Integrated **Photonics Manufacturing:** This includes the development of generic integration platforms and foundry models. Addressed technologies comprise III-V semiconductors (e.g. InP), TriPleX and SOI, Monolithic integration of functional materials into the more mature platforms to enhance functionality, CMOS post processing; assembly, alignment and fixation, RF processing in optical domain (microwave photonics), Integration of electronics and integrated photonics. Also photonics technology will be combined with e.g. fluidics and mechatronic technologies. Dutch businesses and knowledge institutes are also actively developing innovative packaging technologies (including micro-assembly, housing, integration of electronics and photonics, and fiber-to-chip coupling) for application of next generation photonic IC's (PIC's). TU/e uses PICs for example for gas (environmental) sensors, communications, (neuromorphic) computing, Lidar, biomedical imaging, metrology, quantum communications.

• **Photonics Integrated circuits for advanced computing:** Photonic integrated circuits are increasingly being considered for new computing paradigms, such as neuromorphic computing and quantum computing, for example as dedicated co-processors, accessible through the cloud. Such computers will outperform traditional (super)computers for specific tasks, such as deep learning for AI. Commercialization of these technologies has been taken up already globally, e.g., by Lightelligence, Lightmatter and Luminous for neuromorphic computing, and by PsiQuantum and Xanadu for quantum computing, often backed by large investments. In the Netherlands, TU Eindhoven and University of Twente have relevant research lines on these topics, and the start-up QuiX is bringing PIC-based quantum computing to the market. Given the PIC technology manufacturing ecosystem present here, and recognizing that AI is mostly driven by efficient hardware, the clear opportunity is to develop a key link in the value chain of AI, thereby creating a strategic position in a huge future growth market. Opportunities that build on Dutch strengths.

• **Optical sensors:** photonic structures, often integrated within fibers or optical circuits, make it possible to identify or characterize their environment in a non-destructive and contact-less way. Examples include the identification of materials through their spectral fingerprint (e.g. gas sensing, fluorescence and reflectance spectroscopy), the measurement of displacement, stress or acoustic waves (e.g. with fiber-Bragg gratings for example for the security of bridges) and 3D imaging systems for the automotive industry and for security applications. It also includes integrated optical biosensors for the early detection of diseases and monitoring the progression of diseases.

TNO works on combinations of Artificial Intelligence AI, vision and optical sensing for applications in Smart Industry, Agrifood and Security.

• **Computational imaging (CI):** CI aims to combine and jointly design optics and computational post-processing algorithms in order to realize a breakthrough in performance well beyond traditional imaging and sensing. There is a large diversity of CI-based imaging technologies, with e.g. lensless imaging, phase retrieval, digital aberration correction, high-dynamic range imaging, motion blur deconvolution, and tomography to name a few. The latter has been key for advanced medical imaging with its CT- and MRI-scanners. Nowadays, Computational Imaging has become ubiquitous in everyday life through a.o. smartphone photography and autonomous driving. In the semiconductor industry, shrinking dimensions and increasing 3D complexity of IC architectures necessitate well-controlled manufacturing together with dedicated wafer metrology (both inside as well as outside the lithographic scanner); further metrology advances will require new breakthroughs in specific CI technologies as the ones mentioned above.

• **Generation of Light:** Sources include integrated lasers, solid state green LEDs, photonic crystal lasers and materials for light conversion (such as phosphors and quantum dots), quantum cascade lasers, VCSELs, supercontinuum sources, plasma sources, ultra-short pulses, high power lasers, THz sources, nano- and, non-linear optical sources, free-electron based sources, broadband VUV sources, fast tunable nanosecond lasers, new scintillation materials, On-chip amplifiers and lasers based on rare-earth ion doping, working at different wavelengths ranging from the visible till the mid-IR.

• **Light propagation, manipulation and detection:** Integrated optical circuits, micro resonators, optical fibers, photonic crystal waveguides, plasmonics and metamaterials, spatial light modulation by refractive, diffractive and adaptive optical elements, scattering, beam shaping and deflecting, optical cloaking, temporal modulation of light or slowing of light, filters, non-linear optics and switching of light.

Nanostructures for light interaction at sub wavelength scales (nanophotonics), interaction of light with waves, such as with plasmons, phonons, or light waves, coherent control, light for manufacturing (lithography) or data storage, light for medical diagnosis and treatment, optical tweezers, bio-optics, new materials for collecting light and optimizing interactions.

Novel types of spectroscopy and microscopy, also with sub-diffraction limited resolution, (remote) sensing, new imaging systems, highly efficient light harvesting structures, optical antennas, optical signal processing, near-field detection, interferometry and metrology, CMOS single-photon detectors and imagers and plasmon detectors.

• **Photovoltaics and sunlight driven chemical processes:** solar panels play an increasingly important role in energy production, driven by innovations that push efficiency up, and module cost down, for Si panels. To break through the efficiency ceiling of Si photovoltaics, current research focuses on nanophotonic light management strategies, and novel materials such as perovskites. At the same time, photonic engineering promises architecture-integrated photovoltaics.

Sunlight-driven chemical processes use sunlight as an energy source for the production of green hydrogen and converting CO2 into C1 gases and fuels. When successful this will contribute to the world climate goals. Optical technology is needed for sensing and additional illumination.

• **Quantum optics**

Quantum networks connecting and entangling long-lived qubits via photonic channels may enable new experiments in quantum science as well as a range of applications such as secure information exchange between multiple nodes, distributed quantum computing, clock synchronization, and quantum sensor networks. A key building block for long-distance entanglement distribution via optical fibers is the generation of entangled photonic telecom-wavelength qubits. Such building blocks, and many other quantum related systems, are now developed and analyzed at TUDelft and TNO, cooperating in QuTech with world-leading companies like Microsoft.

In May 2020, Minister Ingrid van Engelshoven and European Commissioner Mariya Gabriel launched Europe's first public quantum computing platform: 'Quantum Inspire', developed by QuTech. Quantum Inspire makes the quantum computer accessible to everyone and is the first in the world to use a quantum processor made of scalable 'spin qubits'.

• **Quantum photonic technologies:** that is, technologies which use the quantum nature of light to achieve computation, communication or sensing tasks at levels not possible with classical technology. These technologies rely on integrated optics both as an enabling technology and as the core component. Applications of integrated photonics for quantum technologies include photonic quantum information processing, quantum key distribution, quantum random number generation, quantum metrology including inertial sensing.

• **Virtual Reality, Augmented Reality**
The technology of virtual and augmented reality (AR) has already come quite far, but not yet far enough. The stability of the image, the field of view, hand tracking and the ability to move tools along with it, still need to be improved to enable a broad use in industrial and medical applications. AR combined with special cameras and spectrometers can make things visible that are normally not visible to the human eye. Clever optical design is required to ensure that all of this can be fitted into a headset. Optics Netherlands is active in developing these technologies jointly with industrial partners. In the last years this field shows accelerated activity with a spade of new introductions. Several companies and institutes are active in headsets and displays , e.g Brilliance (headsets), and TNO (microled displays).

• **Next-generation optical metrology:** metrology for nanolithography will benefit from innovative coherent light sources, detectors and optical paths, at wavelengths from the infrared down to soft-X-ray. Researchers in the Netherlands develop such methods, systems, sub-systems and components. In order to meet the semiconductor metrology challenges of tomorrow, we need to be successful in many optics-related disciplines and we need to integrate that in practical, robust and versatile systems.

• **3D-metrology for robots**
The digitization of the manufacturing industry is one of the central themes for the Netherlands. This transformation is necessary in order to increase productivity, address the growing scarcity of qualified personnel, and promote future economic growth, making industry more sustainable. Smarter production processes make it possible to use raw materials more efficiently. The transformation to a digital industry requires new production, metrology and communication technologies within which photonics plays a major role.

Optical 3D-sensors are used to measure dimensions, position and orientation of objects during manufacturing and automated assembly processes, as the "eyes" of the robots. The rapid development of LIDAR is also finding new applications in robotics, drones and agriculture.Some of the building blocks of this type of systems are available; however the integrated intelligent “robot & sensor” systems are still to be developed. We foresee that the future availability of affordable intelligent robots, equipped with several different types of sensors, will be a huge boost for application of robots in the manufacturing industry.

• **Sensors for AgriFood**
The need for more food grown in a sustainable way, depletion of resources, pollution, reducing waste and the ever rising cost of fertilizers and pesticides are all drivers towards a new way of sustainable precision farming and a more efficient supply chain. Information and hence sensors play a pivotal role in this. Photonic sensors are very well suited for remote sensing in qualitative and quantitative ways. Hyperspectral imaging, (IR) spectroscopy, photoacoustic gas sensing, speckle imaging and biosensors are examples. It is possible to measure ammonia and methane in air, sugar content in fruit,or the composition of milk directly after milking this way. Also biosensors could replace time consuming lab analysis in food processing. There is a special program on precision agriculture in the PhotonDelta growth fund with a range of new sensing solutions being planned both to determine

growth conditions, soil health, post-harvest produce conditions and composition. Among others One Planet in Wageningen is doing R&D and there are already several startups, like Mantispecta (NIR sensors), and Spectrik (ammonia and other gas detection).

• **Laser Satcom**

The ever-increasing demand for bandwidth and the number of devices and processes that need to be connected implies that existing forms of information exchange will be insufficient within a few years. The development of future multi-terabit communication technologies will be based on optical infrastructure and technology. Technologies needed to address these issues range from laser satellite communications in support of the growing Internet of Things to integrated photonics devices that help increase communication capacity and reduce energy consumption in data centers and consumer communications around the world.

A number of companies and organizations are already working on such networks. Europe's space agency ESA, for instance, has the EDRS, the European Data Relay System, which is being built in cooperation with Airbus Defence and Space. Companies like SpaceX and Facebook also have ambitious plans with regard to such space-based networks.

Dutch companies, such as VDL, DEMCOM Focal, TNO, Lionix International and Nedinsco, are active in this field. And there are several Dutch companies involved in space technology, like Airbus Defence and Space Netherlands, Hyperion Technologies and ISIS, who are good at building satellites. FSO - Instruments has been founded to commercialize Laser Satcom optical-communication components, sub-systems, and terminals. Research on different aspects of optical communication, for both terrestrial and space applications, is performed by the 3 technical universities (Delft, Twente, Eindhoven) and also at KNMI, VU Amsterdam and Leiden University.

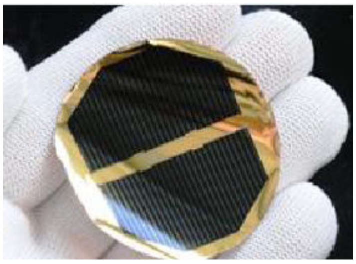
• **Data and telecom transceivers and photonic systems**

The exponential growth in broadband demand and speeds is continuously pushing the developments of communication infrastructure across all domains (from fiber to the home(FTTH) to long haul networks). Underlying deployment of enhanced optical links is innovation in transceiver performance. These find themselves being used in growing numbers in data centers and FTTH installations as well as in more traditional locations in metro and long-haul networks. For data centers, the need for photonic solutions close to the switching electronics is driving a shift to co-packaged optic engines (CPOs) to lower energy consumption of the switching fabric in large data centers. More recently, optical switching is being considered as an alternative for electronic switching in data centers. Such a paradigm shift will require huge investment in new types of PICs with enhanced performance and significantly more complex packaging solutions.

2.2 Developments in present and future markets and societal themes

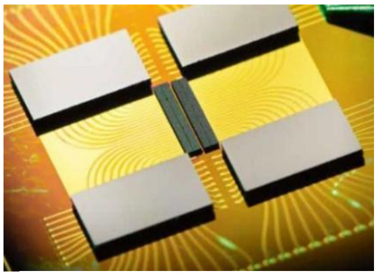
Photonic technologies are applied in a wide range of new products, providing solutions for many societal challenges (SCs).

1. Climate – including energy and water



Slowing and mitigating climate change has a high global priority. Together with all other European countries, The Netherlands has agreed to cut the greenhouse gas emission levels by 40% compared to 1990 levels, to realize a 27% energy savings compared with the business-as-usual scenario and to realize a share of 27% of renewable energy consumption by 2030. Meeting these agreements requires the transition to a sustainable, smart energy system built on renewable energy sources and large-scale energy savings. It also asks for flexible energy networks.

The transition to a sustainable, smart energy system builds on renewable energy sources such as solar-, wind- and bio-energy. Light is one of the important energy sources. Photonics, therefore, plays a crucial role in the energy transition. Novel photovoltaic materials, new manufacturing techniques, and improved light management in solar cells boost the efficiency of solar cells towards the Shockley-Queisser limit. Development of flexible form factor of solar cells is also allowing easier integration into infrastructures. Solar fuels and photochemistry driven by sunlight are another important topic.
Photonics also contributes to other renewable energy sources, for example for the photonic monitoring of mechanical stability in windmill propeller blades.



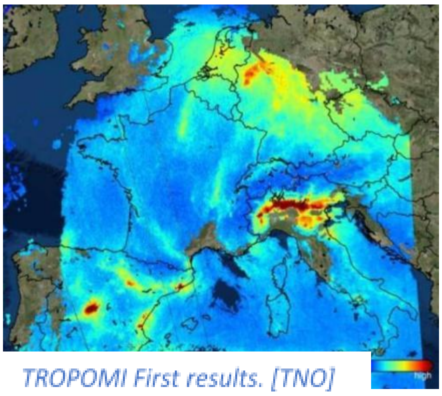
Massive Parallel Interconnect [University of Eindhoven]

Large-scale energy savings can be accomplished through, for instance, energy-efficient buildings and offices, appliances, datacenters and (ICT) networks. Smart window optical technologies can help to control the heat flow in buildings. Optical sensors can track movement and therefore add to smart and energy saving lighting and heating systems. Integration of energy efficient solid state lighting technologies (O)LED into various applications is having a significant impact in reducing global energy consumption. Energy efficient appliances have energy saving photonic chips.

Measurement of net radiation to estimate regional evaporation of water. [Hukseflux Thermal Sensors]

Societies around the world face, or will face , the effects of global warming in the coming years. Part of the efforts of the societies are focused on the reduction of global warming itself ('mitigation'). The other part is focused on 'adaptation', which is a necessity due to the altered **weather** patterns and a rising sea level. These adaptations need to take place at the right moment and in a smart and efficient manner. As such, we can help prevent or reduce the risk of natural disasters, social and economic damage and political tensions.

Photonics plays a significant role in climate change and water by means of advanced detection technologies, such as earth

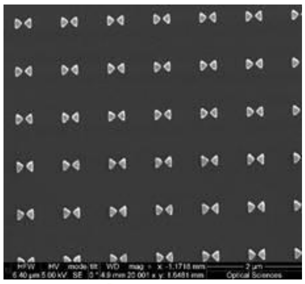


TROPOMI First results. [TNO]

observation using advanced optical pollution detection instruments (such as TROPOMI) and **water quality & air safety analysis**. Waveguide-based Surface enhanced Raman spectroscopy (i.e., waveguide SERS) is for example being developed for the detection of pollutants in drinking water.

Cloud-connected, smart photonic sensing systems for pervasive community-based environmental pollution monitoring and real-time citizen alert on local pollution levels and related health risks (H2020 ICT call 37).

Further examples are for structural integrity monitoring in large constructions like dikes, bridges and flood control dams. Photonics technology will be used for real time monitoring of water movement, sediment transport and offshore structures e.g. windmills. FBG (Fibre Bragg Grating) sensors can for example be used for the monitoring of groundwater flow. The national science agenda has recognized these challenges as well as giving a start-impulse to the NWA route "meten & detecteren". In this route metrology for both climate and health technologies will be developed.



Optical nanoantenas for SERS [Mesa+]

2. Sustainability

The world population is increasing rapidly. The United Nations projects that the population will grow from 7.9 billion people in 2022 to 8.5 billion in 2030 and 9.7 billion in 2050. How to sustainably feed 10 Billion people?
Not only does the demand increase, the demand also changes. More people can afford more nutritious products. And more consumers chose healthy food, as a response to a growing share of people with healthcare problems, such as obesity. This is all happening in an environment where climate change accelerates and so does the pressure for more sustainable AgriFood production processes with reduced nitrogen emission.

Photonics for precision farming. [Avantes BV]

To cope with these challenges the agri-food sector needs to become more efficient, more sustainable and more diverse. Photonics sensors and novel light technologies **improve the efficiency of the agriculture sector**. New lighting architectures in greenhouses can enhance the growth of crops and **precision farming** using optical sensors can optimize the harvest per square meter.

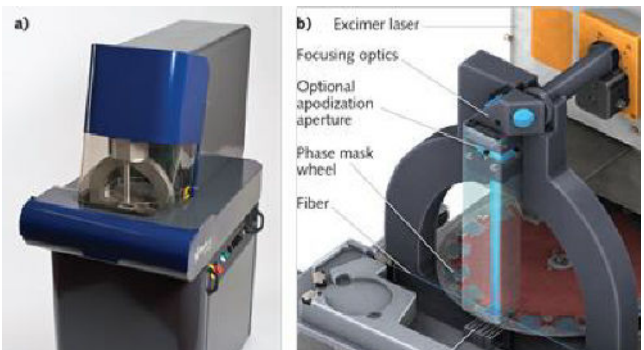
Precision farming is a growing market where The Netherlands has a strong position through industry and universities (Wageningen) and other research organizations.

Photonic sensors (using Infrared spectroscopy) also monitor the **quality of food** for food safety purposes, for example of packed food, fruit and crops before and during harvesting, storage, transport and in the shop. Another example is the food processing Industry. In the Netherlands, we have a 9 B€ national industry that exports food processing machines, who have identified challenges in yield monitoring which could be solved with light-based sensors.

To change the worldwide trend of extensive use of raw materials and thus exhaustion of natural resources, a radical change towards a **circular economy** is needed. The current linear model of 'take-make-use-waste' needs to be replaced since it already is insufficient to fulfill the world's needs. The circular economy is an economic system in which products, components and raw materials or commodities can be reused and natural resources can be maintained up to a sustainable level.

Photonics contributes to the circular economy by means of advanced (opto-mechatronic) measuring techniques, leading to increased performance of production processes (smart industry) and reduction of waste. The development of sustainable technologies such as future developments in solar energy benefit from improved measurement and analysis technologies based on photonic components.
Furthermore, it leads to precision instruments assisting the development and producing products 'first time right', as well as to develop inherently reusable products. Furthermore, photonics provide novel and more insights in growth conditions in agriculture, helping the reduction of nutrients needed and therefore lowering the footprint. As one third of the food grown in the world is lost along the supply chain, novel technologies to detect pests , molds or desears or damage can help a lot and optical technologies are well suited to do so. By integration they can become small and robust and suitable to fit on robots or drones.

Digitization of the industry ("Smart Industry") is crucial for sustaining international competitiveness, employment, product innovation and a greener industry. It



will enable a fully digitized and connected value chain from supplier to customer with the emphasize on high-precision, cost-competitive and resource-efficient production, fast and flexible mass customization and new (data-driven) services. This transformation is driven by new manufacturing and communication technologies.

Photonics is a vital enabling technology for “**Industry 4.0**” as well. Machinery with high-precision lasers replace the conventional machines used to cut, weld, solder, drill and structure metals, plastics and composites.

Ultrahigh-resolution cameras, 3D imaging, optical sensors and augmented reality improve precision in the production processes. These photonic technologies enable autonomous robots and predictive maintenance, using fiber optics as the industrial communication network.

NORIA tool, developed by Hittech based on TNO technology, enables Somni to produce Fiber Bragg Grating based sensors for medical and industrial applications.

Furthermore, the power consumption of data centers and networks can be decreased by employing energy saving photonics in data interconnects, transmission and switches.
Finally, photonics can function as hardware accelerators that directly implement, e.g., machine learning algorithms, with much higher efficiency than is fundamentally possible with current electronics.

A few of the emerging technologies for digitization of the industry are listed below:

- High-power lasers for industrial processing
- Fiber optics as the backbone of Industrial Internet.
- Use of optics for additive manufacturing (3D printing) and mass customization.
- Advanced optical sensors, 3D machine vision and 3D imaging for high-precision production processes and autonomous robots.
- Predictive maintenance enabled by optical sensing
- Optical computing underlying artificial intelligence and smart robotics
- The industrial production of micro and nanomaterials and structures using high-performance lasers.
- Photonic integrated circuits to make mass-manufacturable photonic solutions.
- Rich visual communications such as ultrahigh-resolution cameras, augmented reality and 3D display technology

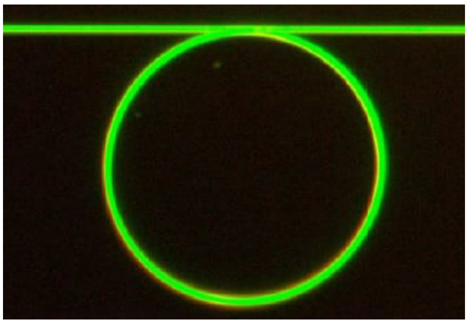
Extreme ultraviolet (EUV) lithography systems offer solutions for a smaller technology node (smaller feature size, smaller transistors, both faster and more power-efficient) in the semiconductor industry. And photonic integrated circuits make mass-manufacturable photonic solutions possible.

3. Health

The demand for healthcare is increasing at a fast pace. The number of people with chronic diseases increases as a result of the aging population. Better healthcare has led to an increase in life expectancy. This increase in demand for healthcare is exerting a constant pressure on healthcare systems.

Therefore, prevention rather than treatment of diseases is of growing importance. Medical diagnostics moves from current, cost-intensive, centralized diagnostics after the onset of a disease, to the detection and prevention at the earliest possible stage by new (handheld) diagnostic instruments. Handheld diagnostics and treatments make point-of-care diagnostics, as well as better critical care, possible. Miniaturization of medical devices can bring healthcare from the clinic towards the practitioner/patient and even further directly to a patient's home. Bringing the best possible healthcare to the patient is important. Non-invasive diagnostics and surgery are therefore one of the biggest challenges in need of a solution. Other trends include an increasing focus on the individuals through personalized healthcare and prevention based on an individual's biomedical information and e-health supporting a healthier lifestyle. Exposome is a new trend in this field, where through knowledge of the lifelong exposure health could be predicted.

Philips Digital Pathology



Rare-earth doped Al2O3 ring to make "active" biosensors with increased sensitivity. [Source: University of Twente]

Medical photonics is one of the major application domains of photonics. There are many ways in which photonics supports the medical field.

Photonics components are part of many medical devices for treatment and diagnostics. Therapeutic systems and systems for in vivo and in vitro diagnostics comprise a combination of photonic components (lasers, imaging sensors, detectors), micro-electronics, mechanics and software. These photonic components include endoscopes, therapeutic laser systems, medical imaging systems, CR systems, ToF-PET and PET-MRI, fluorescence diagnostics systems, label-free biosensors (Twente region, Lionix) coherent detection, optical coherence tomography systems, SPECT, Raman (CARS) based diagnostic systems, photoacoustic imaging technologies. Miniaturization of these photonic components in medical devices is an important challenge for future R&D in photonics.

Advanced (medical) photonics also offers non-invasive monitoring, for example through skin with light – spectroscopy, and minimal invasive surgery using fiber probes. Optical instruments are developed for super-resolution, long-time live-cell imaging, and full organoid imaging for developing and studying disease models, which can improve screening methods. Augmented and virtual reality based on photonic technologies offer opportunities for medical training, surgery and remote healthcare, and also e-health makes use of imaging sensors.

Bio-sensing using integrated photonics is one of the promising application areas, which makes instant and accurate (viral disease) diagnosis possible. Companies and institutes are developing photonics enabled bio sensing tests that can be used for fast real-time (and on site) detection of Covid-19 which can also be used for the detection of other viruses. This is regarded as the holy grail in medical diagnostics. A sample from the patient, such as saliva or blood, can be taken and analyzed from wherever the patient is located, and delivers results within minutes.

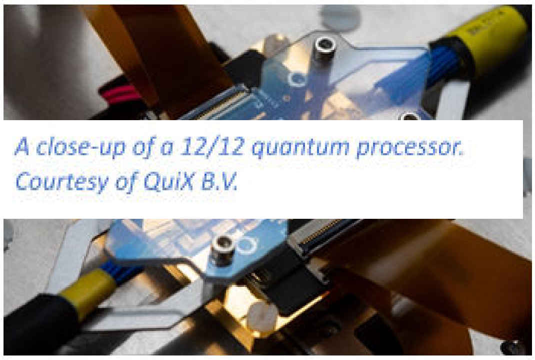
4. Security

Realizing a secure physical and data infrastructure is one of the major societal challenges we are facing today. Our society is more connected every day, and we are sharing more and more information over the internet. New applications reveal information on our health conditions (e.g. e-health) and financial status (e.g. online payment transactions, online insurance) and consumption patterns (e.g. retail information). Also, our devices, machines and vehicles are increasingly connected under the frame of smart homes, smart factories and smart cars. Protection of privacy, individual identity and secure data networks must be guaranteed.

Photonic sensing and imaging technologies are used for higher levels of security and safety. Here sophisticated surveillance and encryption technologies are used as well as in logistics. In The Netherlands, a (photonic) chip technology has been developed for identification checks on passports and other documents. Innovations such as near field communication are also bringing new applications within reach.

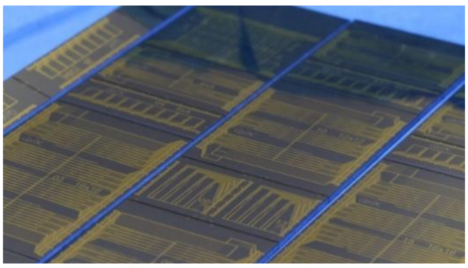
Quantum technologies are a key component of a future safe society. Photonics plays a key role in all three branches of quantum technologies, which are: *computation*, *communication* and *sensing*. All three sectors are predicted to undergo substantial growth above GDP growth in the coming years.

For *computation*, large-scale tunable integrated photonic chips play the key role in photonic quantum information processing, where single particles of light are directly used as the information carriers. Such optical systems enable computations to be carried out faster than is possible using modern supercomputers. The key enabling technology here is low-loss, high component density optical chips. This activity is now being pursued commercially in the Netherlands in the Twente cluster. Integrated photonics is also used in ion trap and cold-atom quantum computing architectures.



A close-up of a 12/12 quantum processor. Courtesy of QuiX B.V.

For *communication*, the key applications are quantum key distribution, quantum random number generation and quantum authentication. Quantum key distribution enables the transmission of information with guaranteed security. It relies crucially on fiber optics, on free-space optics for short-distance links and quantum satellite connections, and on integrated optics at the sender and receiver nodes. Quantum random number generation underlies many cryptographic applications. Quantum authentication uses the inherent fragility of quantum states to read out physical keys in an non spoofable way for access at high-security locations or as digital keys to authenticate messages.



A series of QuiX quantum photonic processors.

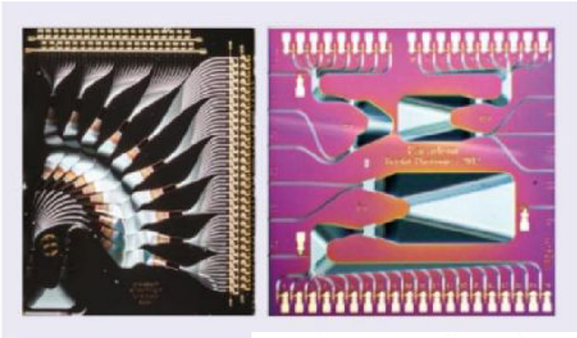
Finally, quantum *sensing* can be used for example for inertial navigation. This plays a key role in replacing GPS navigation in GPS-denied environments, such as in submarines.

The physical infrastructure also needs to be protected from treats. Dikes, roads and bridges need to be protected from environmental impact and can be monitored by photonics sensors. Security in open seas is also a global concern. With piracy and hijacking occurring all too often, international navies have started focusing more on littoral operations ('brown-water navy') and less on high-seas operations ('blue-water navy'). The combination of Dutch shipbuilding, sensor and, in particular, radar technologies, results in extremely efficient solutions developed in collaboration with distinguished technology research centers at knowledge institutes such as MARIN, TNO and Dutch technical universities.

With financial support from the MESA+, we started a project to detect COVID-19 biomarkers with a portable integrated optical sensors. The sensor will detect simultaneously, in a matter of minutes and with high sensitivity and selectivity the COVID-19 virus, the antibodies generated and the IL-6 cytokine. Thanks to the multiplexing capability provided by wafer-level microfabrication, multiple tests could be run simultaneously. A proof-of-concept of a portable readout module is also being developed within the project.

5. Society of the future

The Netherlands is a worldwide hub for goods and people from around the world. Our country has unique expertise in logistic processes and how to design them in the best possible way. The challenge is, however, to mitigate the side effects of mobility and transport, including CO2 emissions and pollution, noise and to ensure traffic safety. This explains why new forms of transport (like electric cars and trucks), new logistical processes (like bundle & share), and disruptive technologies like 3D printing are potential areas where solutions can be found. The development of new safety and navigation systems will provide possibilities for new types of services including connected car functions, **smart mobility** and intelligent transport.



Readout system for Fiber Optic Sensors [JePPIX]

For the automotive industry, a photonics-based sensor technology can be integrated in the form of light-based detection and ranging (LIDAR), using either mechanical or integrated optical steering for in-car communications, monitoring, warning and vision.

Beyond fifth generation (5G) mobile, wireless optical communication will be able to solve some of the challenges ahead for the automotive industry. In autonomous driving communication with a low latency is required, with extremely robust, secure network connections to edge computers operating in the cloud.

Laser Satellite Communication [TNO]

In aerospace, examples of photonic systems include optical solutions deployed in RADAR, LIDAR (for autonomous vehicles) and space communication. This includes integrated photonics based smart, redundant and reliable sensing fiber optic systems for extreme and harsh environments.

The development of the future multi-terabit communication technologies will be based on optical infrastructure and -technology. The ever increasing demand for bandwidth, and the amount of devices and processes to be connected, will mean that standard forms of information communication will become insufficient within a few years from now. Technologies required to address this issue will range from laser satellite communication to support the rising Internet of Things, to integrated photonic devices which will help to increase the communication capacity and to lower the energy consumed in internet datacenters around the world.

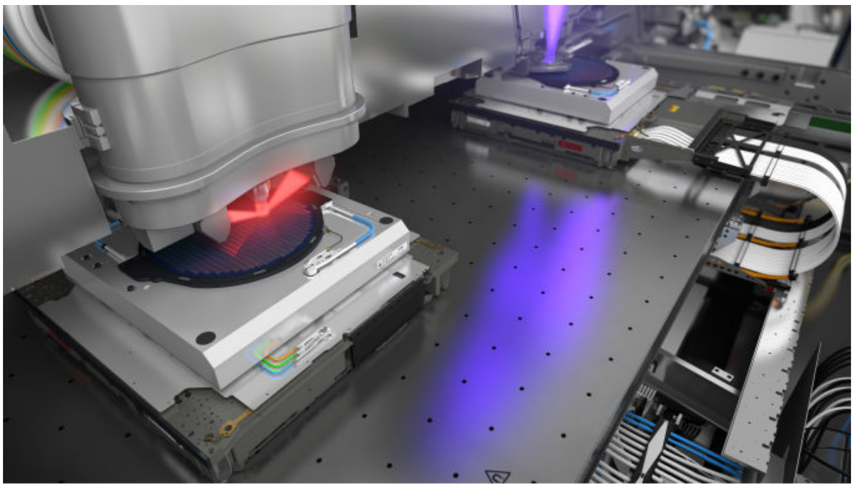
Technological development changes the world rapidly. New skills are required due to automation, robotization and digitization, both at work and for daily life activities. Photonics can support an **inclusive society**.

Augmented-reality can assist maintenance engineers with online-manuals and provides new training opportunities. Optical operator support systems may help employees to assemble products.

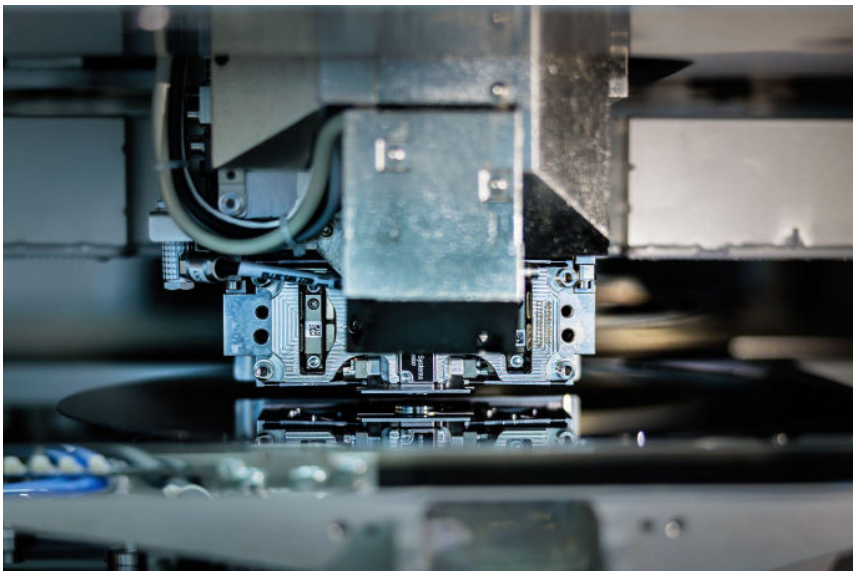
Augmented Reality [TNO]

Photonics can also improve the connectivity of people. Connectivity within homes and the connection from homes to the outside world depends on high-speed communication technologies such as optical fiber and optical transceivers. In addition, wireless communication technologies enable users to connect to the network. These technologies make use of (photonic) ICs (Systems-on-a Chip, SoCs).

Innovative full colored bulb based on a lightguide for high quality color and white (Signify).

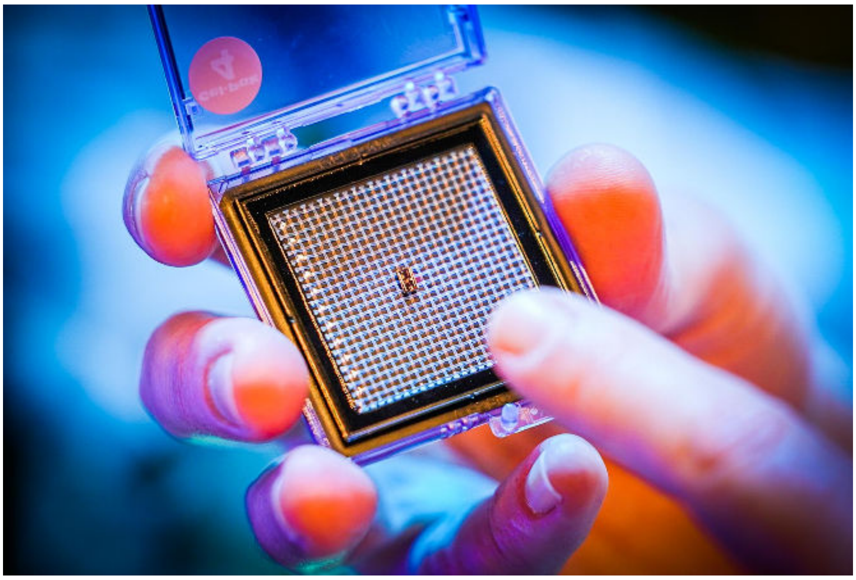


Schematic view of the metrology and exposure stages in an EUV lithography system (ASML).



YieldStar scatterometry for accurate and fast semiconductor wafer metrology (ASML).

Adjustment of equipment for high volume lens replication (Anteryon)



SMART Photonics in Eindhoven is an Indium Phosphide foundry of photonics integrated circuits (photo credit Dutch Technology Week)

2.3 Conditions and milestones for this roadmap in 2030

In the recent European Commission and European Investment Bank report on “Financing the Digital Transformation: Unlocking the value of photonics and microelectronics” (2022), photonics technologies are regarded as “one of the essential key enabling building blocks for the digital transformation of Europe”.
The European coordination of photonics is exemplary: the Horizon2020 Photonics Public-Private Partnership (PPP) was created to build on the strengths of the European photonics sector and by that reinforce the competitiveness of the European industry. For this purpose, the European Commission joined forces with the photonics industry, represented by Photonics21, and the research community. The result has been a dynamic and productive partnership which has been recognized as the best PPP in Horizon2020 by the Commission’s independent evaluators and demonstrated by the PPP’s impact on jobs and growth in Europe.

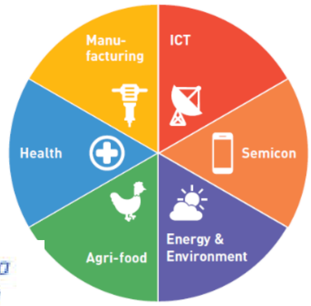
General issues such as establishing standards and regulatory frameworks have to be realized on an European level. Some specific questions and boundary conditions for implementation of the Dutch national roadmap on Photonics are:

- The link between the academic and industrial knowledge in national application- and technology-oriented programs.
- The development of a plan for educating photonics professionals with 21st century skills at all academic levels.
- Energy and CO_2: The government and regulatory bodies play a large part in the development of energy and CO_2 reducing related technology, through CO_2 pricing, standards for compliance verification and new regulations to force the reduction of CO_2 output. Simultaneously the public sector plays an important role in promoting and implementing energy saving technology e.g. in lighting.
- Agro and Food: Spread technology via involvement and education of farmers, and support technology uptake by smaller farms.
- In Healthcare: Open up the healthcare market to new technologies, and improve access to healthcare markets for innovative SMEs.
- In Circular Economy: Focus innovation on sectors that will ultimately contribute the most at the least net cost.
- Innovative and inclusive (and digital) society: Strengthen the Smart Industry ecosystem, support a powerful and secure telecommunications infrastructure and facilitate pilot production lines.
- Last but not least, we cannot afford to drop the ball when it comes to the link between academic research and actual innovation and industrialization. We have a leading technology ecosystem and we need to keep executing on it in all fields.

2.4 Dutch vision and synergy with National Agenda Photonics

This photonics roadmap is based on our vision on the future of photonics: an overview of the most relevant research and development themes for the Netherlands, with an outlook on benefits for society and industry.

This Roadmap is in synergy with the National Agenda Photonics where we mentioned a shortlist of the main *application* fields of photonics and relevant areas of research and technology development for the Netherlands:



National Agenda Photonics [NAF]

- Photonics in Medical diagnostics: Biophotonics, including compact sensors for home care, high-end diagnostics for early detection of major diseases, and photonics for exposure monitoring.
- Photonics in ICT, digitization of society and industry: Increasing communication capacity by "fiberisation", and decreasing the energy need of data centers by integrated photonics
- Photonics in Semicon; metrology and imaging systems for semicon industry, and Smart Industry
- Photonics in Manufacturing: companies that make displays, lighting, production machines and measuring instruments for the production process (e.g. sensors)
- Photonics for Energy and environment: more energy efficient photovoltaics, climate monitoring by remote sensing, efficient lighting.
- Photonics for AgriFood: sensor systems for precision farming, and efficient lighting for optimizing production of food; sensors for (food) quality monitoring

Further elaboration of these topics is needed, including prioritization and synchronization with priorities at European level. This synchronization will also help to increase the Dutch role in European photonics projects. PhotonicsNL is part of a new project, starting in 2021, together with the consortium of NextPho21 and Photonics21.

3. Priorities and implementation

The Netherlands is strong in research of technologies, which underpin photonics, and leading in the development of industrial integration platforms (LioniX International, SMART Photonics, PHIX). At the same time photonics products are often sourced from global suppliers with manufacturing bases outside the Netherlands. This means important links in the value creation chain are often outside of the Netherlands. As technologies become increasingly sophisticated, an apparent opportunity arises for Dutch companies to operate on the complete value chain. Realization of this ambition needs some coordinated actions:

- Photonics research and development must center around realizing novel techniques and devices that can contribute to societal challenges. A well-coordinated effort with innovation potential, starting in academia, can lead to start-ups, and that possibility should be emphasized and stimulated.
- In our national ecosystem we need companies, virtual or physical labs and R&D programs aimed at integrating and testing PICs into modules and systems for practical applications. Basically a link between DOC and PhotonDelta .
- World-leading concepts in photonics are being developed in the Netherlands. Support is needed to accelerate innovation throughput to the industry, assisting companies with up-skilling of the workforce and providing access to state-of-the-art manufacturing technologies.
- Creating regional Digital Innovation Hubs, a.k.a. fieldlabs, or other ecosystems to develop innovative new photonic solutions. This extends beyond the photonic technologies to include the adjacent technologies: high speed electronics, mechatronics systems, and systems for large scale data processing. What we need to build in our national ecosystem: companies, virtual or physical labs and R&D programs aimed at integrating and testing PICs into modules and systems for practical applications. Basically a link between the DOC and PhotonDelta ecosystems.
- Innovations are required in assembly technologies to enable competitive advantage from within the Netherlands. Paradigm shift in the cost model for hardware assembly can lead to the reshoring of manufacturing. This includes the complete process chain of “Additive Manufacturing” from CAD model to the product, and the development of wafer scale processing for both optics, and smart systems incorporating combinations of optics, photonics and electronics.
- Several initiatives (on both national and regional level) have been set up by the clusters , Photon Delta, and PhotonicsNL and Optics Netherlands. Photonics is now acknowledged to have a priority status on a national level (ministry of Economic Affairs and Climate) and regional level (provinces and development agencies) leading to joint efforts by the clusters to thrive for an increased level of innovation in photonics with involvement of a broad network between academia, knowledge institutes and industry. It is essential that these actions continue.
- PhotonicsNL, Optics Netherlands, PhotonDelta and NWO will give support with setting up, and maintaining the Photonics Roadmap.
- Valorization projects will be carried out together with TNO/GTIs including projects with SMEs and links with IPCs and other Innovation Funds to secure commercialization and market introduction for innovative components and systems.
- Photonics is a driving force in the fundamental research programs of NWO, and the EU program Horizon Europe, in which European Partnership for Photonics is a candidate European Partnership in the area of digital, industry and space.
  Photonics (light based technologies) is described as an essential building block for the digital transformation and for a green and healthy future in Europe. This partnership aims to speed up photonic innovations, securing Europe’s technological sovereignty, raising the competitiveness of Europe’s economy and ensuring long-term job and prosperity creation. By 2030 Europe will have maintained leadership in core and emerging photonic technologies

The specific photonic calls and increased budget for photonic research, in which fundamental research results are transferred to applications within collaborations between industry and knowledge institutes (e.g. AMOLF, ASTRON, SRON, and all Dutch universities) will increasingly be executed within the framework of these programs.

- The Knowledge and Innovation Agenda 2018-2021 underlines that photonics as a key technology has an impact on almost all societal challenges. If we want to make an active and targeted connection with social and departmental agendas (V&J, Defense, I&M, VWS, the food agenda, the energy agenda, the climate agenda) and we want to get more results from research, then we need to build a more open and accessible infrastructure, based on open innovation collaboration in recognizable Photonic Technology Centers (PTCs) with jointly established R&D agendas and top facilities. The Photonic Integration Technology Center is a first, important example of this, which will enable tight cooperation between knowledge institutes and industry, and will play a key role in the establishing of a European Digital Innovation Hub activity in the Netherlands.

3.1 Implementation of this roadmap in public-private partnerships and ecosystems

The Netherlands has an excellent position to bring photonics into various markets. We provide a high scientific level in important photonic segments (Dutch universities and NWO initiatives) and a highly qualified high-tech industry with specific expertise in Biophotonics, Imaging and Sensing, Integrated Photonics, Nano-electronics and Mechatronics, optical design and engineering for space and other challenging environments. Dutch internationals like ASML, Philips, Signify and OCE/Canon, are large players in the photonics area and the Netherlands also contains more than over 120 SMEs embracing photonics for innovation (See overview in Chapter 4).

As such, a smart photonics ecosystem is active in the Netherlands addressing the complete value chain; three cluster organizations jointly coordinate the ecosystems: PhotonicsNL, DOC, and Photon Delta. Together these organizations regularly initiate activities including joint promotion and business development of the Dutch photonics industry (in international exhibitions and trade missions), definition of joint research plans in photonics, and joint synchronization meetings with the government.

Photonics NL: The national association for optics and photonics professionals in the Netherlands. The main goals of PhotonicsNL are to increase the level of awareness of the importance of photonics for our economy, to increase the knowledge of photonics at all levels of education and last but not least to build a strong and valuable photonics network in the Netherlands, in Europe and beyond.

In the Netherlands a large number of SMEs and a few large players are active in photonics, supported by a good knowledge infrastructure. These parties operate in various and different market segments and various (own) networks. Cohesion and structured cooperation are important factors for building a strong competitive position. This could include collaboration in the field of design, manufacturing and integration into modules so that we can generate a greater impact nationally and internationally. The "enabling" nature of photonics only then really comes to life.

Through cooperation at national level and through the use of their strong contacts in Europe, PhotonicsNL wants to prevent the fragmentation of the growing number of photonics initiatives. Together with PhotonDelta and Dutch Optics Centre, they form the Dutch photonics platform. PhotonicsNL also works on increasing awareness on gender issues in Photonics. Together with the Women in Photonics Group (60+ participants), we organize yearly symposia and lunch meetings and help young women to find jobs and get into contact with the Photonics industry in the Netherlands.

Dutch Optics Centre: is a consortium of knowledge institutes with involvement of more than 100 High Tech companies from all over the Netherlands. It was initiated by TNO and TU Delft with the aim of boosting Dutch industry in the field of optics and opto-mechatronics and increasing utilization of Dutch science through joint R&D. The Netherlands is unique in the field of optics and opto-mechatronics, with a leading position in science and industry. Within the Dutch Optics Centre TU Delft, TNO and other knowledge institutes provide excellent research facilities and team up with a world class manufacturing industry; producing opto-mechanical components for high-precision products like satellites, telescopes, microscopes, and inspection instruments. By joining forces in R&D, developing prototypes and eventually forming product consortia a strong Dutch optomechanical ecosystem is created, generating value for industry and science. This initiative is well aligned with the Dutch government's ambition for large-scale Public-Private Partnerships.

PhotonDelta is a growth accelerator for the Dutch integrated photonic sector with the mission to realize a € 1 billion industry in The Netherlands by 2026. To realize this goal, a team of experts actively supports its partners with strategic investments, knowledge and network, resulting in an acceleration of the development and manufacturing of integrated photonics solutions through innovation, reducing time-to-market, and creating economies of scale.

PhotonDelta was initiated in 2016 as an open-innovation project launched by Eindhoven University of Technology, after which it soon expanded its scope to national level with Eindhoven, Twente, Nijmegen and Delft regions, involving companies and public investors in order to form a public-private partnership at the end of 2018. During the relatively short period of its existence, PhotonDelta has established itself as a leading innovation hub with a dedicated investment fund of €236 million.

Over the past few years, PhotonDelta has invested considerable amounts of capital and energy into organizing and financing the core of the Dutch integrated photonics supply-chain, ensuring they make it through the valley of death. A number of start-ups have transformed into mature companies, each with their own distinctive technological propositions, setting the foundation of a strong Dutch supply chain that is able to design, manufacture, package and test high quality integrated photonic solutions based on InP as well as TriPleX (SiN) technology, making The Netherlands the obvious choice for companies that are looking to innovate with integrated photonics. This specifically concerns SmartPhotonics, PHIX, LioniX International and component manufacturers EffectPhotonics, SurfiX and Technobis.

Besides supporting SMEs and bigger organizations that are looking to innovate their products with integrated photonics, PhotonDelta also provides startups with the opportunity to join its Startup Studio programme (under development, to be launched in Q4 2020 / Q1 2021). This programme will enable startups to utilize the technological platforms that have been created, as well as a wide range of other services such as seed and growth capital, access to libraries of IP and technological building blocks, access to European network and partners like PhotonicsNL, expert knowledge that has been accumulated through i.e. the creation of customer-driven roadmaps (e.g. IPSR-I, LIDAR, bio-sensing), human capital and recruitment services, and infrastructure i.e. through the Photonic Integration Technology Center (PITC).

Amsterdam Science Park - ARCNL and AMOLF: The NWO institute ARCNL is a public-private partnership between VU, UvA, NWO and ASML. They perform fundamental research with a strong application perspective towards breakthrough technologies for extreme ultraviolet (EUV) lithography. Photonics is a major theme in their work, and they have strong expertise in EUV light sources, optical metrology, laser systems, computational imaging, spectroscopy, and optics in general. They collaborate with the adjacent **AMOLF** institute ca. 60 researchers in the Center for Nanophotonics, which addresses nano-optical research questions for imaging and metrology, solid-state lighting, nano-optics for classical and quantum information processing, and solar technologies of the future (with UvA and TNO, photovoltaics, and with Differ, solar fuels). Optics is a main pillar of the Amsterdam hub of QuantumDelta.

SOLARLab The national SOLARLab consortium unites all academic photovoltaics groups and TNO Solar, and coordinates PV research in the Netherlands. It is led by the NWO Focus Group "Light Management in New Photovoltaic Materials" at AMOLF that develops new photovoltaic materials and solar cell architectures with a focus on optimized light capture and conversion. Other NWO focal points working on solar technologies are the Groningen NWO Focusgroup on organic photovoltaics, and the TU/e-DIFFER effort on solar fuels.

Holst Centre: is an independent R&D center created by TNO and IMEC, that develops wireless autonomous sensor technologies and flexible electronics, in an open innovation setting with industry and in dedicated research trajectories. Photonics is central to many of the technology programs including large area flexible (medical) imagers, free form lighting and signage, sensors, virtual reality displays and next generation manufacturing processes. With PITC there is now a strong focus on integrated photonics programs

IMEC: has become more important the last few years and has settled good contacts in Wageningen and Nijmegen for societal solutions with their technology. They are offering public private partnerships.

Solliance is an initiative to combine forces in research for development of the next generation, thin film solar cells. Solliance was founded 2010 as a joint venture of ECN, TNO, Holst Centre and IMEC, together with the academic partners TU Eindhoven, University of Hasselt, TU Delft, Twente University, Gendt University and Forschungszentrum Jülich. Through joint developments programs with industry, and an application focus, Solliance can play a significant role in global research into the solar technology of the future.

Some Fundamental research centers (not all clusters contain groups from more than one university):

Photonics research at the **MESA+ Institute for Nanotechnology** of the University of Twente has always been a key area of interest. The success of this strategic research orientation was recognized by the establishment of the Applied Nanophotonics (ANP) cluster of the involved MESA+ research groups. This group of over 100 researchers addresses nano-optical research questions collaboratively where possible. ANP researchers currently work on a variety of subjects such as integrated photonics, photonic crystals, complex wavefront shaping, advanced microscopy, photonic manufacturing techniques, quantum photonics, and photonic information processing. Together with industry, knowledge is developed for instance on free-form light scattering, photovoltaics, and for various sensing applications such as in water quality monitoring. The research infrastructure and cleanroom facilities of the MESA+ Nanolab play a pivotal role in ANP's activities.

An important focus is the development of TripleX-based photonic integrated circuits following the generic photonic integration approach pioneered by LioniX International in collaboration with the Nanolab of the University of Twente. The technology is commercially available for both academics and industry through e.g. MPW runs. The University of Twente was also a major partner in setting up the national Photon Delta initiative.

Integrated Photonics: represents a major research cluster at TU Eindhoven, with seven research groups and >100 researchers actively involved in fundamental and applied research in materials, devices and systems. An important focus is the development of InP-based photonic integrated circuits following the generic photonic integration approach pioneered at TU/e. This technology is commercially available through Eindhoven-based scale-up SMART Photonics and the EU platform JePPIX. TU/e also played a pivotal role in setting up the national PhotonDelta initiative and the Photonic Integration Technology Center.

An important focus is the development of TripleX based photonic integrated circuits following the generic photonic integration approach pioneered by LionX International in collaboration with Mesa lab of University of Twente. The technology is commercially available for both academics and industry through e.g. MPW runs.

The IEEE Photonic Society Benelux is a sub-chapter of the international Photonic Society of the IEEE and founded in 1996. The fields of interest are lasers, optical devices, optical fibers, and associated lightwave technology and their applications in systems and subsystems in which quantum electronic devices are key elements. The society is concerned with the research, development, design, manufacture, and applications of materials, devices and systems, and with the various scientific and technological activities which contribute to the useful expansion of the field of quantum electronics and applications.

Institute for Lasers, Life and Biophotonics (LaserLaB) in Amsterdam is groundbreaking scientific research based on the interaction of light with matter, spanning from the research on atoms and molecules to the investigation of living cells and tissue and sustainable energy sources. Within LaserLaB, research is conducted in close collaboration between physicists, chemists, biologists and physicians. LaserLaB Amsterdam is hosted at the VU University, with participating research groups at the UvA, AMC and VUmc. LaserLaB is a founding partner of the new imaging center VU University medical imaging center. LaserLaB Amsterdam is part of LASERLAB-Europe, an Integrated Infrastructure Initiative of the European Union, forming a consortium of the 33 major laser centers in Europe

3.2 Linkage with other innovation instruments (e.g., public purchasing and risk investment)

The results of the NWO-perspectief and several KIC programmes of NWO have sustained and strengthened the position of Dutch Photonics in the last years and will do in the years to come. The JePPIX organization assists users around the globe to get access to advanced fabrication facilities for Photonic Integrated Circuits.

NWO has granted and supported the past years various IPP programmes (via Perspectief Programs of TTW, calls within the KIC such as Consortia in Photonics with Taiwan and the calls Key Enabling Technologies, Wind and solar energy innovations, and ENW and via IPP programmes of NWO-Science and NWO-Institutes:

- Free Form Scattering Optics. This program enables high-tech optical devices that contribute to energy efficacy, climate change, internet-of-things, food and water quality and quantity, and security, in the interest of rendering the unstoppable worldwide sustainable urbanization.
- LINX (Lensless imaging of 3D nanostructures using soft-X-rays) programme has started in 2018 and is a collaboration between 5 academic partners and 7 industrial users (budget 4.2 M€). The central theme of this programme is the development of imaging and metrology methods for nano-structures and -devices.
- Synoptic Optics program will use all properties of light for disruptive improvements in instruments concepts with high application potential on societal challenges. Collaboration

between 8 knowledge institutes and 13 industrial users (start 2020, budget 4.1 M€, industry contribution of 1.8 M€ in cash + in kind)
- Physics for Nano Lithography (PNL) programme focuses on the fundamental physics involved in current and future key technologies in nanolithography, primarily for the semiconductor industry (budget 9 M€ with equal contributions of 4.5 M€ from NWO and ASML, respectively).
- OPTIC (Optical coherence; optimal delivery and positioning) is a collaboration of five academic partners and six industry partners to improve the optical functionalities and efficiencies of innovative high-tech devices. Three major relevant Dutch high-tech industries — semiconductor nanofabrication, lighting and satellites — share common optical technology challenges for their devices. Mathematics, optics and physics researchers in academia work on novel optical coherence technology in collaboration with the industrial partners to address these challenges. OPTIC takes a step forward by the combination of freeform optics on the macroscale and wavefront shaping on the microscale.
- MEDPHOT (Photonics Translational Research - Medical Photonics) programme wants to develop a light-based counterpart of a PET scan and is a collaboration between three UMCs, 12 industrial partners, four universities and TNO (total budget 5.3 M€).
- 3D Nanoscale Imaging (3DNI) is a programme aiming to develop technology for making 3D images, super-fast, and on the extremely small nanometer scale. This programme is a collaboration of three universities, three UMCs, and seven companies (budget: M€ 3.3).
- Optical Wireless Superhighways: Free photons (at home and in space) (FREE) is a programme in which research into optical free-space communication to replace radio frequencies is done. The programme is a collaboration between five universities, 14 companies, and two knowledge institutes (budget M€ 5.6).
- Steering and sensing sustainable CATalytic reactions with Light (CATLight). This project is a collaboration between AMOLF and University Utrecht in collaboration with six companies (budget ~ M€ 2).

Within NWO the following funding instruments are available for the academic science community: Perspectief (22M€/y), Open Competition (100M€/y), NWO Talent Programme (VI, 165M€/y). Of the projects funded in the domain Applied and Engineering Sciences roughly 15-20% has a strong or direct link with photonics:

Valorization

Next to these research oriented programs, valorization is of great importance because of the risk of not reaching the business with all the exciting photonics technologies. The gap between technologies and business is a well known bottleneck on a European level.

There are generic valorization instruments in use, managed by Dutch Enterprise Agency, NWO and Regional Development Agencies and European Union (SME Instrument). It is best that the technologies use these as much as possible.

- Programs from Dutch Enterprise Agency that give specific attention to small companies, Seed Capital program, Vroege Fase Financiering, Innovatie Krediet.

- PhotonDelta has leveraged the interest by the financial sector in several investment rounds, resulting in multiplications of the initial capital injections committed by PhotonDelta. As a result, there has been an increase in trust in the production promise of the front and back-end foundries.

- Also within NWO there are specific programs for valorization. Next to these academic programs, there are Take-Off (Feasibility studies, early stage routes), and demonstrator (technology development) programs (4M€/y) and possibilities for industrial partnership programs (IPP). A good financing climate is of great importance.

- Also projects like NextPho21 and the future project under Horizon Europe are valorization programs with for example specific Photonics4 workshops with end users in various sectors.

3.3 Collaboration in and leverage with European and multi-national policies and programs

Photonics in Europe is positioned in Digital Industry and Space, destination 4. Digital and emerging technologies for competitiveness and fit for the green deal. A second link can be found within Digital Europe, with the development of Digital Innovation Hubs.

Expected impacts addressed: #19 (Green), #20 (Data), #21 (Industrial leadership and autonomy), #22 (Digital and emerging enabling technology sovereignty), #23 (Space)
Objective: establish European technology and data sovereignty and supply chains by developing cutting edge photonics technology platforms and manufacturing of key photonics components and systems to enable the digital and green transformation of the European economy and society.

Achievements sought / targets:
- Foster world leadership in photonics: by incorporating new technology concepts and platforms such as digital photonics, computational 3D imaging, mixed reality, integrated photonics, micro- and nanophotonics, plasmonics, metamaterials, quantum optics.
- Digitize European Industry: provide critical photonics core technologies to strategic European industry sectors

As digital key enabling technology photonics is synergistic with other technologies and application areas. Thus, close cooperation with other partnerships and Horizon Europe clusters is sought. These include among others Quantum technologies, KDT, Made Europe, AI, data and robotics, Smart Networks and Services, Global competitive space systems, HPC, Smart Farming, Towards zero-emission road transport, Clean aviation.

4. Partners and process

4.1 Partners in this roadmap from industry, science, departments, regions and cities

Over the last years more than 200 Dutch industrial and scientific partners, active in Photonics, have been requested to provide input to this roadmap. Many thanks to these photonics colleagues for providing us with their views and knowledge, in random order.

Paul Schuddeboom (NWO), Andre Fiore (TU/e), Oded Raz (TU/e - IPI), Wilbert IJzerman (Signify), Kevin Williams (TU/e), Frans Harren (RU), Ron van der Kolk (PhotonicsNL), Martijn Heck (TU/e), Stefan Witte (ARCNL), Ton van Leeuwen (UVA AMC), Silke Diedenhofen (NWO), Petra Wicherink (PhotonicsNL), Femius Koenderink (AMOLF), Ewit Roos (PhotonDelta), Roland Kuijvenhoven (Te Lintelo Systems), Urs Staufer (TUD), Theo Rasing (RU), Silvania Pereira (TUD), Bart de Boer (Delta

Diagnostics), Sonia Garcia Blanco (UT), Eddy Schipper (RVO), Jelmer Renema (QuiX), Bart Snijders (TNO/DOC), Hans van den Vlekkert (LioniX, QuiX), Pepijn Pinkse (UT, MESA+, ANP), Eric de Leeuw (Diamond Kimberlit), Benno Oderkerk (Avantes), Martin van der Mark/Jean Schleipen (Philips), Klaas Jan Damstra (Grass Valley), Kees van den Bos (Hukseflux), Jan Boers (Dino-Lite), Stefan Bäumer (TNO), Pieter Kramer (Laser 2000), Gerlas van de Hoven (Genexis), Hans Naus (Camlin Technologies), Jeroen Wehmeijer (Lambert Instruments), Willem Hoving (Anteryon), Christoph Keller (Leiden University), Paul Urbach (TUD), Babette Bakker (TNO), Allard Mosk (Utrecht University), Huub Salemink (Radboud / TUD), Marnix Tas (Sioux CCM), Marco Beijersbergen (Cosine), Egbert-Jan Sol (Smart Industry), Hugo de Haan (Innophysics.nl), Michel Verhaegen (TUD), Remco Nieuwland (SOMNI), Marco Snikkers (Ocean Insight)

4.2 Process followed in creating and maintaining this roadmap (with role of SME)

The first original version (2012) of this roadmap was made based on a large number of contributions from industry, academia and institutes, including SMEs. The 2015 version was based upon the original as well as the 2013 and 2014 updates.

Parallel to updating the 2015 version of the HTSM photonics roadmap, a Strategic Research Agenda was prepared in the framework of an EU CSA project "Innopho21" in which the Photonics Cluster Netherlands (today called PhotonicsNL) was a partner.

In 2018 the update of the photonics roadmap has been set up based on the Societal Challenges, as described by the Dutch Top Sectors.

In 2020, the update of the Photonics Roadmap is based on the 2018 version and the new set of Societal Challenges, as described by the Dutch Top Sector.
The editing of this roadmap is coordinated by PhotonicsNL – Ron van der Kolk and Petra Wicherink, Optics Netherlands/TUDelft - Anke Peters , NWO ENW – Silke Diedenhofen, NWO TTW - Paul Schuddeboom, Eddy Schipper (RVO) and Hans van den Vlekkert (LioniX International), in collaboration with many others. A set of recent Dutch, European and global documents on Photonics has been used as reference (see footnotes).

5. Investments[1]

Roadmap	*2019*	2021	2022	2023	2024
Industry	*10.5*	14	14	15	15
TNO	*4*	1.2	1.3	1.4	1.6
NWO	*3.5*	3	4	4	4
Universities	*4.1*	8	8	8	9
Regional development agencies and provinces (excluding TKI)	*1*	8.5	8.5	8.5	8.5
Grand total	***23.1***	**34.7**	**35.8**	**36.9**	**38.1**

European programs within Roadmap	*2019*	2021	2022	2023	2024
Industry	*0.6*	3.5	3.5	3.5	3.5
TNO	*0.35*	0.45	0.45	0.45	0.45
NWO		1.2	1.2	1.2	1.2
Universities and Academic Medical Centers	*3.7*	6.8	6.8	6.8	6.8
EZK co-financing of European programs	*0.75*	0.75	1	1	1
European Commission co-financing	*0.75?*	12	12	12	12
Grand total	***6.15***	**24.7**	**24.95**	**24.95**	**24.95**

Starting points Roadmap:

- Industry: Baseline of 4M Euro (see Roadmap 2015 – 2018) plus PhotonDelta and Dutch Optics Centre as PPS in the Netherlands.
- TNO: To be added shortly additional numbers on photonics in quantum.
- PhotonDelta:
    - For the Industry there is an estimated 10M Euro per year in PhotonDelta alone
    - Departments and regions (Excl. TKI) is 8.5M Euro per year
    - Universities approximately 3M Euro per year
- Universities: Comparing to former years this including an average contribution of 3M Euro per year for PhotonDelta.
- The budget for R&D at the universities, more specific PhD students, is evenly distributed over 4 years. Assuming also 70k in salary per PhD and 30k material cost.
- The contributions from industrial partners can consist of in cash, in kind and use of equipment.

Starting points European programs within Roadmap

- European programs within Roadmap update after start of Horizon Europe. Was 60 M Euro funding in Horizon2020 (2014 – 2019). Among which 24 Companies, 3,5M Euro per year in average. Assumption is that the companies equal this amount.
- European programs within Roadmap: Universities also quantum photonics research TUD is included with 3M per year and photonics related research at Academic Medical Centers.
- Key Digital Technologies program as successor of Ecsel.
- Yearly European Commission co-financing: The 0.75M Euro of the former Roadmap is unclear.

[1] R&D in public-private partnership, including contract research; all figures in million euro cash flow per year (cash plus in-kind contribution)