2020

Photonics Roadmap

PhotonicsNL NETHERLANDS

Dutch Optics Centre
a TNO and TU Delft initiative

PhotonDelta
Gateway to Integrated Photonics

NWO
Netherlands Organisation for Scientific Research

Rijksdienst voor Ondernemend Nederland

HTSM Roadmap Photonics 2020-2023, version September 2020.

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 3 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. The National Photonics Agenda, the higher TRL level of Integrated photonics initiated by PhotonDelta and the further clustering of the optics community through PhotonicsNL and Dutch Optics Centre. Also the bridging of photonics, as an important enabling technology, with multiple application areas and technologies, for example Quantum Technologies and Artificial Intelligence. Last but not least the increased interactions of the Dutch Photonics Ecosystem with international partners.

Photonics as an 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. Photonics has also a major role in the *Groeifonds* proposal for Quantum Technologies.

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.

The Covid-19 crisis has shown what role Photonics can play when it comes to tackling of issues like for example fast screening and cleaning of surfaces.

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.

1. Societal challenges and economic relevance

Photonics is the key 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 and at many SMEs and start-ups in the sector.

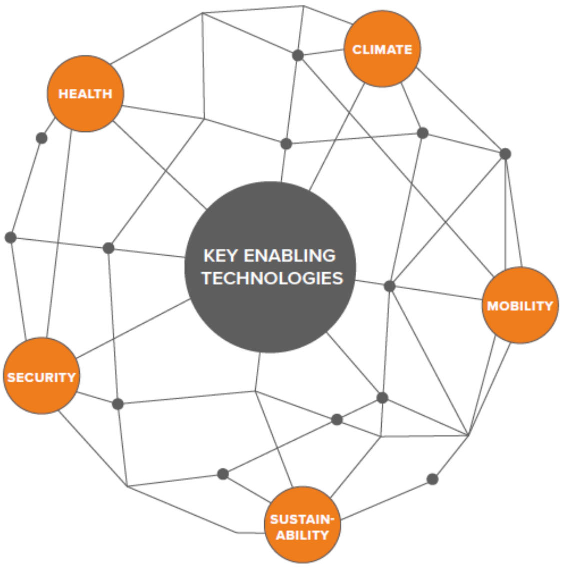
In this document, we formulate the Photonics Roadmap, in which we want to unite our colleagues from the academic world, business and government. Our roadmap is based on the following starting points:

- Strengthening excellence. Dutch photonics research is internationally leading in various fields. It is important to maintain this position and, where possible, to strengthen it further. We also have to be careful that we don't miss the step between basic science and applications, that would limit innovation potential.

- Substantial contribution to societal challenges. Photonics currently has a strong impact in solving crucial contemporary societal challenges, for example the challenges related to Covid-19.
- Increase return from research. We must strive to valorize where possible much of the scientific knowledge and infrastructure.
- Attention to educating human capital. A highly educated population is crucial in realizing our ambitions whether we focus on excellent research or to the social and economic use of knowledge.
- Joint responsibility for the process by science, government and companies.

1.1 Societal challenges addressed in this roadmap (with examples)

Photonics is the physical science and the technology of light (photon) 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 gases, more energy efficient photonic solutions are been developed. This includes very efficient light sources, (O)LEDs, energy generation by highly efficient solar cells and more energy efficient data centers by application of photonic ICs. Photonics in climate change can also be used for advanced detection technologies, such as earth observation using advanced optical pollution detection instrument (such as TROPOMI) and water quality & air safety analysis.

2. Sustainability

Sustainability is a key driver for research and innovation in smart industry and smart farming. In a world with a growing population, sustainable industrial and agricultural solutions are essential. Photonics is used in Agro and Food through remote sensing for precision farming, LED-lighting in horticulture, vision for phenotyping, robotics for overall efficiency, optical sensors for water-, crop- and livestock monitoring, such as for the present nitrogen-crisis, for pollution, generation of gases from agriculture, for farming, to measure the quality of milk or gases emitted by livestock.
Furthermore, in the ideal circular economy with 0% wastage and 100% re-use for all production and products, photonics plays an important role in the advanced (opto-mechatronic) measuring techniques, for increasing performance of production processes

(smart industry) and lowering waste (first time right design) with sensors, lasers, EUV lithography and 3D displays
Last but not least, no other technology has achieved comparable levels of increase of energy-efficiency as Photonics has for Communication and Computing. With a factor of 2 every 2 years (see Koomey's Law, for example), Photonics plays a key role in contributing to sustainability.

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. In case of Covid-19, Photonics can enable all of this, on-site, which is essential.

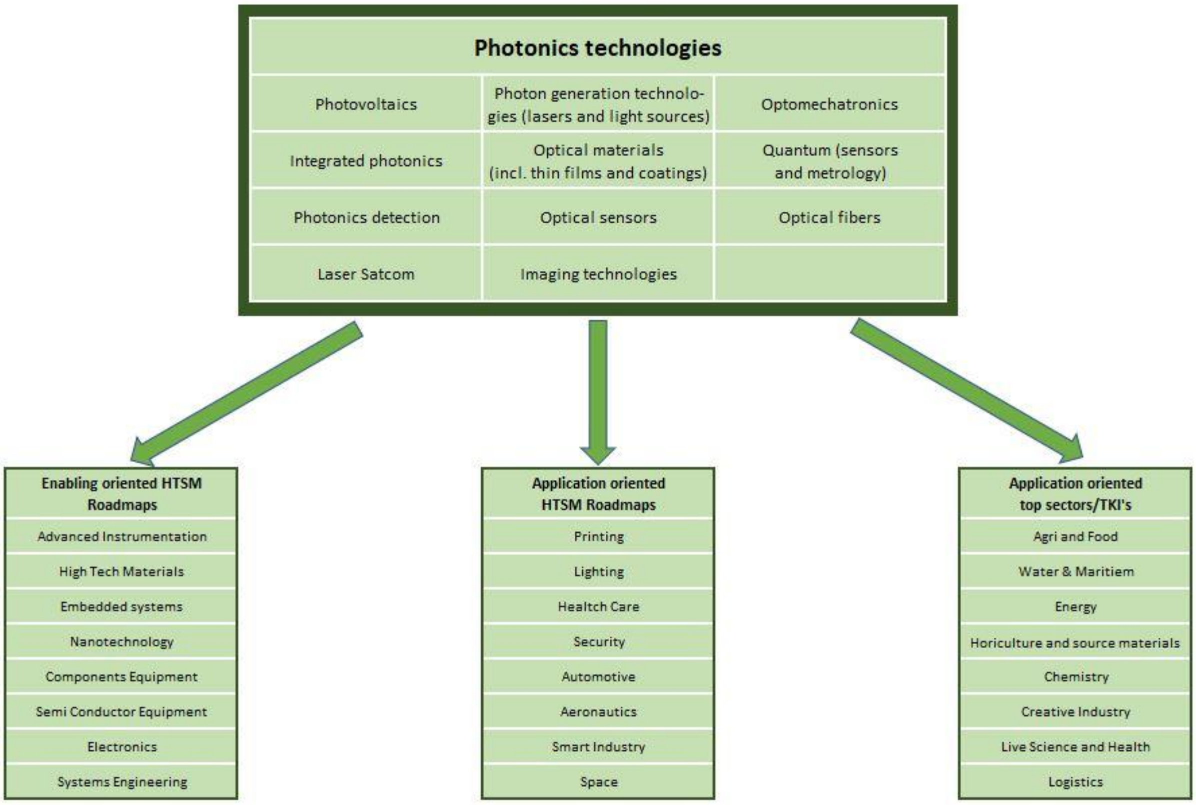
4. Security

With photonic sensing and imaging technologies we can realize higher levels of security and safety. For example, sophisticated surveillance, authentication and encryption technologies are used in the communication field as well as in logistics (e.g. nano-dust detection, Tera Hertz 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 automotive and aerospace metrology and communications, low-latency networking technologies for autonomous mobility (e.g. LIDAR), as well as the future multi-terabit communication technologies based on optical infrastructure and -technology. From laser satellite communication to support of the growing Internet of Things, to integrated photonic devices increasing the capacity needed and lowering the energy consumed in internet datacenters around the world and more.

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



1.2 World-wide market for this roadmap, now and in 2025 (with examples)

While the global photonics market has reached €600 billion, according to Europe's Age of Light, the estimation is that only 20% of the potential power and benefits of light technologies have been unlocked. With a compound annual growth rate (CAGR) of 6.2%, the European photonics industry is growing four times faster than the European 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 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.
An estimated 290 companies that are based in the Netherlands are active in photonics according to the Nationale Agenda Fotonica (NAF), with a total turnover of €4,2 billion. In the coming years more than 85 percent of the companies expect to achieve annual job growth of 5 to 20 percent or more.

The high growth expectations are reflected in the initiatives taken at the regional level. The provinces of Noord-Brabant, Overijssel and Gelderland collaborate in order to build on their strength in the field of integrated photonics aiming for thousands of new jobs in the future.
The leverage photonics offers to the manufacturing industry and end markets is considerable. The EU Report Leverage of Photonics concludes that around 10% of the European economy depends on photonics for its competitiveness, both in terms of markets and jobs.

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 for commercializing photonic based quantum technologies.

> “Front-end monolithic integration of different functional materials on the passive silicon nitride platform represents an important effort towards the wafer-level production of fully integrated and tested photonic integrated systems.” [University of Twente]

- The Eindhoven 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 as one of the biggest players in semiconductor manufacturing equipment develops EUV light sources, optical metrology and imaging together with partners from industry and academia throughout the Netherlands (TNO, ARCNL, TU Eindhoven, TU Delft, University of Twente).

- The South Holland region has a strong position in opto-mechatronic 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 there are strong activities in light detection and Photo Voltaics.

For successful positioning within European and worldwide markets we present the Netherlands as a single, coherent, and well-synchronized photonics region. This is enabled by collaborations, network meetings and events, building projects together to link the different parts of the photonics research, and additional budgets specifically for collaborations.

2. Applications and technologies

> 'Open access manufacturing and innovation in photonic integrated circuits is organized by the European JePPIX platform, which is hosted by TU Eindhoven. PhotonDelta is organizing the eco-system which connects technology to supply chains and markets.'
> [TU Eindhoven]

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 is the century of the photon and with the knowledge and technological breakthroughs we are ready to profit from the photonic revolution: achieving a new level in the generation, control and the application of light in many high tech markets where Dutch industry and knowledge institutes will play a prominent role.

2.1 State of the art review (industry and science)

Photonics spans the entire field from coatings, free forms in imaging and non-imaging systems, fiber optics for communication, integrated optics, (near-field) microscopy, (bio)- medical optics, laser technology, nonlinear optics, (remote) sensing, metrology, spectroscopy, nano photonics, plasmonics, metamaterials, to quantum optics and quantum communication.
Dutch academic research is at the forefront of many of these topics and has a strong track record in translating innovations to the Dutch photonics industry. Photonics is an enabling technology for a wide range of applications, and it strengthens the competitive position of Dutch industry in many Top sectors and Roadmaps within the HTSM top sector.

> 'Wageningen University & Research has collected all existing knowledge and expertise in the PhenomicsNL platform to speed up developments in this field.' [WUR]

Currently, there is a wide range of photonic technologies rapidly developing in the Netherlands, with some highlights of the recent achievements of universities, research institutes and companies mentioned in the text boxes.

> 'Optical imaging is the most important imaging modality in Healthcare. Without Optics and Photonics, Healthcare would not exist. Optics in the medical imaging market is larger than for the well-known radiological imaging applications.' [UVA-AMC]

• **Freeforms 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 less components. Applications include remote solid state lighting, photovoltaics, microscopy, advanced spectroscopy, health instruments and lithography. 3D printing of high quality micro optical components enables application of ultra-compact optical systems in large series, e.g. for smart phone cameras.

• **Generic Photonic integration Manufacturing:** 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 matures 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.

• **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.

'The use of wavefront-shaping techniques allows to look deeper and deeper into otherwise opaque tissue'
[University of Twente]

'Increasingly we are working on `hybrid' photonics - simultaneous control of light and other engineered degrees of freedom like motion, spin, excitons,... We believe that this is required for real breakthroughs in photovoltaics (light and charge), quantum (light and spin) and nonlinear photonic simulators (light and excitons).'
[AMOLF]

• **Next-generation optical metrology:** metrology for nanolithography will require coherent light sources at much shorter wavelengths, i.e. EUV and soft-X-rays. Dutch researchers develop such sources, as well as the novel metrology devices and methods required. Frequency comb lasers open up a range of novel spectroscopic techniques, and new metrology concepts.

• **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 often contact-less way. Examples include the identification of materials though 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.

'Our group has developed cutting edge technology based on scattering correction using spatial light modulators, which is used in preclinical research worldwide.'
[Utrecht University]

• **Computational imaging (CI):** also known as 'lensless imaging' is an emerging technology that can lead to a revolution in imaging and sensing. In CI, computer algorithms are used to improve the performance of an imaging system beyond what is possible with optical components alone. This can lead to higher resolution and sensitivity, but also to novel contrast mechanisms and automated detection of features (e.g. in semiconductor metrology, but also for medical diagnostics).

> 'FELIX is large-scale laser facility open to external users. The IR laser provides unique frequency tuning range required for spectroscopic applications such as IRIS (Infrared Ion Spectroscopy). Only 3 or 4 IR laser facilities comparable to FELIX exist world-wide.'
> [Radboud University]

• **New methods and equipment for optics manufacturing:** includes injection molding, diamond turning, magneto-rheological finishing, and robot polishing.

• **New materials:** Includes semiconductors, glasses, plasmonic materials, metamaterials, 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. Such innovations may be expected to enable photonic devices to function with improved efficiency and flexibility, in extreme environmental conditions, and in combination with other key enabling technologies such as microelectronics.

> ''In Eindhoven new materials, devices and circuits for next-generation integrated photonics are developed, together with their application in communication and sensing systems, in close cooperation with PhotonDelta and the European platform'
> [TU Eindhoven]

• **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.

> 'In Twente world-record narrowband integrated lasers are built'
> [University of Twente]

> 'Knowhow position: world-leaders in measurement of polarization and design of diffractive optical elements, well-known experts in wave-front control.'
> [Leiden University]

• **Light propagation and manipulation:** 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.

• **Light interaction:** 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.

'In MESA+ researchers focus on key enabling technologies – nanotechnology, photonics, micro- and nano-electronics, biomolecular and polymer science, advanced materials, lab-on-chip, microfluidics – and exciting new cross-overs.' [University of Twente]

• **Light detection:** 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.

• **Applications of displays:** applications of displays combined with sensors in Virtual Reality and Augmented Reality.

'The development of new tools for large area, noninvasive nanoparticle detection at the nanometer level (<50nm) is of extreme importance for contamination detection in the semiconductor industry. Also, such techniques could be applied to detection and visualization of biological nanoparticles to study weakly scatters such as viruses and exosomes, and for inspection of air pollution due to ultrafine dust (< 100 nm) which has also consequences to human health.' [TU Delft]

• **Photovoltaics:** 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.

• **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 – rely crucially 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.

• **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 variety 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.
Many 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.

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.

• **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 analysed at TUDelft and TNO, cooperating in QuTech with worldleading companies like Microsoft.
Recently, 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'.

• **Artificial Intelligence**
Artificial Intelligence (AI) concerns the ability of machines to demonstrate intelligent behavior. AI is set to transform the way in which we live, work and travel. It will help us improve the competitiveness of Dutch industry and develop innovative solutions which will keep us healthy and safe.
TNO and Dutch Optics Centre work on combinations of AI, vision and optical sensing for applications in Smart Industry, Agrifood and Security.

• **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. DOC is active in developing these technologies jointly with industrial partners.

• **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. 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.

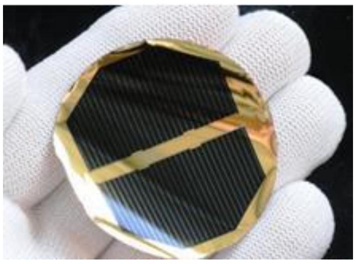
• **Sensors for AgriFood**
The composition of grass can be measured by optical techniques; dry matter, raw protein, raw fiber and sugar. Using this data the nutritional value of the harvested grass can be determined in real-time. A similar technology can be applied for monitoring the composition of manure, which is a real

societal challenge at the moment. DOC and partners, optical instrument developers and end-users in agriculture, are working on this.
Another sensor development is aimed at monitoring soil composition of grassland. A EU initiative for application of optical biosensors for aqua culture monitoring has just been launched and is led by a Dutch company SurfiX BV which is also active in developing test systems for Covid-19.

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



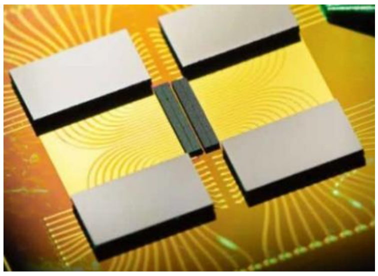
Development of novel photovoltaics based on ultra-high efficiency thin-film III-V cells or on organic materials. [Radboud University]

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.

> ‘This is a unique concept which has been patented through the university. We are seeing interest from several multinational companies for exploitation of this technology. The need for massive parallel interconnect solutions for the data comm market is growing and we anticipate this packaging concept to find its place in the market in the coming years.’
> [TU Eindhoven]



Massive Parallel Interconnect [University of Eindhoven]

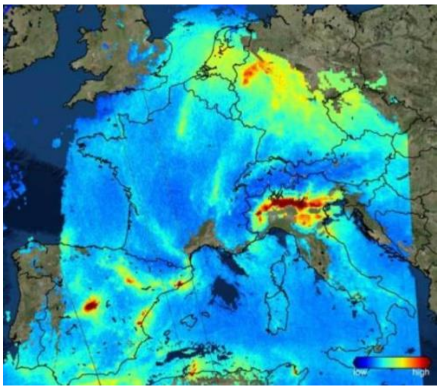
Large-scale energy savings can be accomplished through, for instance, energy-efficient building and offices, appliances, datacenters and (ICT) networks. Smart window optical technologies can help to control the heat flow in buildings. Optical sensors can track movement and therefore add to smart and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

> ‘Energy is growing in importance. It relies on tighter integration of light and materials research.’
> [AMOLF]

Societies around the world face, or will face in the coming years, the effects of global warming. 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.

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

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

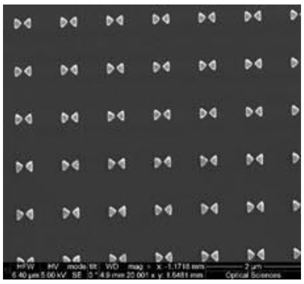


TROPOMI First results. [TNO]

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.

‘State-of-the-art technologies: Self-aligning freeforms and spectral imaging with compact instruments.’ [Cosine]



Optical nanoantenas for SERS [Mesa+]

‘With optical techniques based on scatterometry, it is possible to visualize nanoparticles as air pollution in urban cities, due to ultrafine dust. This is very challenging due to the small particle sizes (10-100 nm). Such technique can improve our understanding about the effects of such particles to human health. understanding about the effects of such particles to human health.’ [TU Delft]

2. Sustainability

The world population is increasing rapidly. The United Nations projects that the population will grow from 7.8 billion people in 2020 to 8.6 billion in 2030 and 9.8 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 for 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 increases 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.

> 'The societal challenge for Agriculture and Food is optimizing the harvest per square meter and the need for nitrate monitoring to avoid ground water levels contamination. This is done by precision farming, the sensor technique used is spectroscopy in the SWIR and NIR wavelength range to measure the chlorophyll and biomass during fertilization .' [Avantes]

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 fulfil 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.

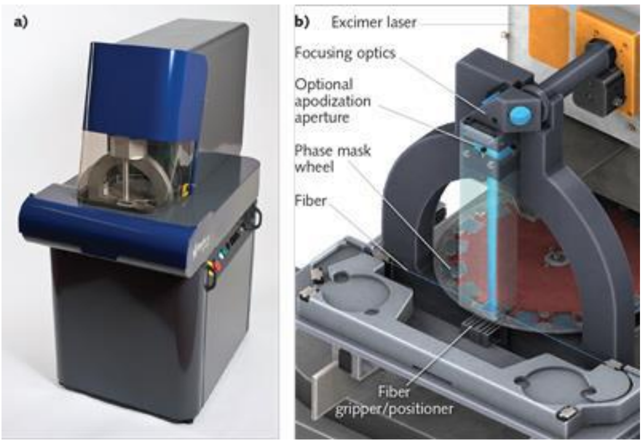
> 'A new and unique gas sensor with which the VOC (volatile organic compounds) load of biogas can be continuously determined by means of infrared absorption spectroscopy.' [Camlin Technologies & Pentair-Haffmans]

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

> 'Photonics devices can monitor food quality and safety during the continuous food chain. From Feed, to Farm to Fork.' [Ocean Insight]

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.

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.



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

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 fibre optics as the industrial communication network.

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.

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.

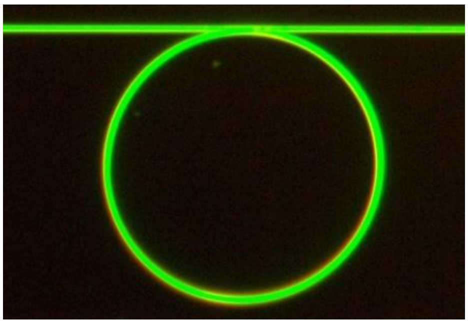
A few of the emerging technologies for digitization of the industry are listed below:

- 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

3. Health

The demand for healthcare is increasing at a fast pace. The number of people with chronic diseases increase 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 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.



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

Philips Digital Pathology

'Main challenges: bridging the gap between technological innovations and clinical applications. Technology and clinical use-case validation requires a tight and early collaboration between technology providers (Philips Healthcare) and care providers (clinicians, hospitals, business developers).'

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.

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

> 'We are developing on-chip integrated sensors based on integrated photonics. The sensors will be multiplexed (detection of multiple biomarkers on the same chip), low cost (based on wafer-level microfabrication), sensitive (clinical relevant concentrations), portable and simple to use (minimum processing of the bio-fluids). We are currently working towards further reducing the limit of detection as well as to developing a low-cost read-out module.'
> [University of Twente]

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, Photo Acoustic imaging technologies. Miniaturization of these photonic components in medical devices is an important challenge for future R&D in photonics.

> 'High market share in handheld digital microscopy: commencing with own / partnering development of value added solutions based on core technology (of supplier in Taiwan).'
> [Dino-Lite]

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.

> 'A test is developed that aims to bring a fast, reliable, low-cost "point-of-care" Covid-19 test to the market.'
> [LioniX International, Qurin, SurfiX]

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 deliver 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.

> 'NXP semiconductors is the market leader in the area of secure chips for passports.'

> '"Silicon based nanophotonic sensors for Shell. Enhanced oil recovery in old fields, and monitoring depleted gas and oil fields for leakage.'
> [Radboud University]

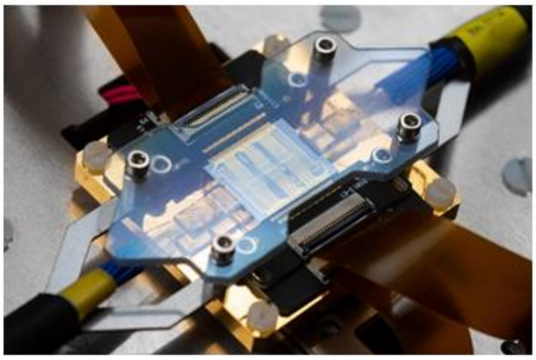
Photonic sensing and imaging technologies are used for higher levels of security and safety. Here sophisticated surveillance and encryption technologies are used as well as in logistics. In The Netherlands, a (photonic) chip technology has been developed for identification checks on passports and other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

> 'Present developments include: "Instrument building blocks; cooperation with academic partners to create new building blocks.'
> [Sioux CCM]

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.

> 'Integrated photonics is key to enable the Netherlands to be a market leader in quantum technologies'
> [QuiX BV]

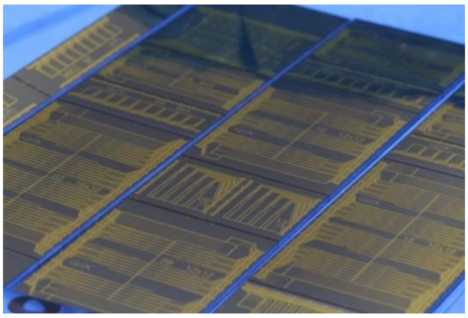
For *computation*, large-scale tunable integrated photonic chips play the key role in photonic quantum information processing, where single particles of light are directly used as the information carriers. Such optical systems enable computations to be carried out faster than is possible using modern 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

> 'Of all quantum technologies, quantum communication is furthest developed , photonics-based and already commercially available'
> [University of Twente]



A series of QuiX quantum photonic processors.

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 unspoofable way for access at high-security locations or as digital keys to authenticate messages.

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.

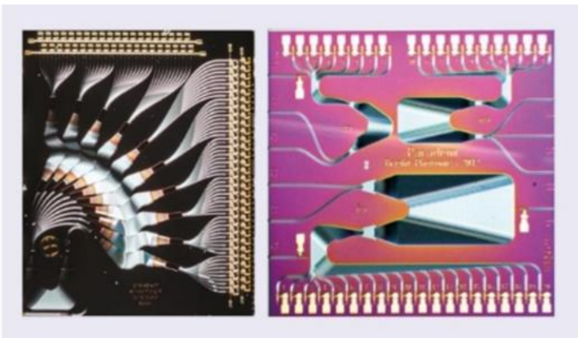
> 'Integration between the academic and commercial ecosystems is key to our success'
> [QuiX BV]

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.

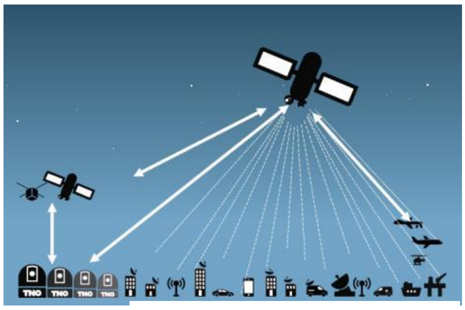
5. Society of the future

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.



Laser Satellite Communication [TNO]

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.

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.

> '"Fiber-based networks also enable the 5G roadmap and the convergence between wireless and wired networks is already underway.' [Genexis]

Augmented Reality [TNO]

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. 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).

> '"Increasing connectivity of people and devices will provide a higher standard of living, provide access to information and education, reduce the cost of healthcare, etc. This will be done by connecting devices, sensors, local computing, cloud computing. Fiber-based networks also enable the 5G roadmap and the convergence between wireless and wired networks is already underway.' [Genexis]

2.3 Questions and milestones for this roadmap in 2025

In the recent European Commission and European Investment Bank report on “Financing the Digital Transformation: Unlocking the value of photonics and microelectronics” (2018), 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.

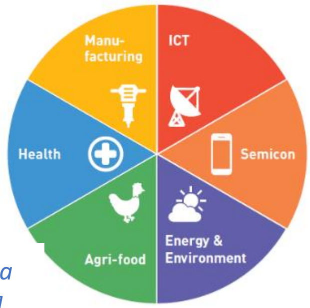
General issues such as establishing standards and regulatory frameworks have to be realized on European level. Some specific questions and boundary conditions for implementation of the Dutch national roadmap on Photonics are:

- 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. Also for Point-of-care diagnostics and immediate results in case of Covid-19.
- 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 (work from home) 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 datacenters 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.

Above all, it is essential that during Covid-19 the Roadmap remains a joint effort of all players in the Dutch photonics field and crucial in the near future, with support from national and regional government.

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 the 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, mechatronical 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 re-shoring 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 Dutch Optics Centre (DOC), Photon Delta, and PhotonicsNL. 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, Dutch Optics Centre, 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 Dutch photonics industry (in international exhibitions and trade missions), definition of joint research plans in photonics, and joint synchronization meetings with 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 optomechatronics 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 economy 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 EUV lithography. Photonics is a major theme in their work, and they have strong expertise in EUV source development, 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 centre 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.

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 the Industrial Partnership Programs (IPP) 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, 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).

- Nanophotonics for solid-state lighting (NSL) aims at achieving fundamental knowledge required to develop efficient solid-state light sources, a joint effort between AMOLF and Philips (budget: NWO 2 M€, contribution Philips 2 M€ and 0.5 M€ TKI-allowance).
- The Gravitation program "Research Center for Integrated Nanophotonics" (2014-2023, 20 M€) aims at developing groundbreaking integrated photonic technology enabling a strong reduction of the energy footprint of photonic interconnect technologies.

Within NWO the following funding instruments are available for the academic science community: Perspectief (20M€/y), Open Competition (20M€/y), HTSM (9,5M€/y, till 2019), Call Sleuteltechnologie (11M€), Talent incentive Scheme (VI, 150€). Of the projects funded in the technology domain 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 know bottle neck 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)

<u>Objective:</u> 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.

<u>Achievements sought / targets:</u>

- 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 vd 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, Dutch Optics Centre / TNO – Bart Snijders, 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)