2018

Photonics Roadmap

Edited by PhotonicsNL, Dutch Optics Centre, Photon Delta and partners. *2018 April 09*

HTSM Photonics Roadmap 2015-2019, update 2018

Contents

1 Societal and Economic Relevance

The world can no longer ignore photonics. Its importance, both economically and socially, is particularly high, as indicated by the answering of parliamentary questions about photonics by the Minister of Economic Affairs (dated August 21st 2017), and the recent addition of the subject Photonics to the spearheads of the Dutch government. The use and application of photonic components, tools and techniques already plays a major role in many sectors, while as 'enablers' photonic devices and photonic technologies form a driving force for innovation. Photonics is therefore recognized by the European Commission as a Key-Enabling Technology (KET). Where the twentieth century can be seen as the century of the electron, many predict that the twenty-first century is the century of the photon.

The expectation is that the importance of photonics in future products will increase further [1]. In this way, we can continue to meet our growing needs in the area of communication, living comfort and health with a minimal burden on the living space. The expected economic growth of the photonics industry is much higher than that of the economy as a whole. For the photonics industry, worldwide growth figures of between 10% and 40% are expected in the next five to ten years [2].

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 a roadmap for the future of photonics, on 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.
- Substantial contribution to societal challenges. Photonics currently has a strong fingerprint in solving crucial problems in contemporary societal challenges.
- Increase return from research. We must strive to make the most of 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.
- Defining centers of gravity based on the above starting points necessarily means prioritization. All parties involved - science, government and companies – have a joint responsibility in this process.

1.1 Societal challenges addressed in this roadmap

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, starting with Christiaan Huygens who has built the first telescope to observe the rings of Saturn and Antoni van Leeuwenhoek who first applied microscopy to

[1] Nederlandse industrie ziet het licht met fotonica, ABN AMRO & PhotonicsNL, Juli 2017

[2] Photonics for the 21th Century study, ETP Photonics21

microbiology. Currently, the Dutch scientists and engineers are still pioneers in researching and developing new technology in the field of photonics. Furthermore, the Dutch contribution to modern society is impressive, however, not always very visible.

Photonics is denoted as a **Key Enabling Technology (KET)** by the European Union [3] and also adopted by the Dutch Top sector High Tech Systems and Materials (HTSM). As innovative technology, 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 [4] :

1. In **Energy and CO2** by the introduction of green photonics, such as very efficient light sources, (O)LEDs, energy generation by highly efficient solar cells and more energy efficient data centers by application of photonic ICs.
2. In **Agro and Food** by remote sensing via satellites for precision farming, LED-lighting in horticulture, vision for phenotyping, sensors for crop and livestock monitoring.
3. In **Healthcare** by the introduction of bio-photonic technologies and their implementation in new applications and services, such as radical novel diagnostic approaches enabling early detection and prevention, and new handheld or portable (integrated) photonic diagnostic instruments enabling point-of-care diagnostics.
4. In **Climate change and Water** by means of advanced detection technologies, such as earth observation using advanced optical pollution detection instrument (such as TROPOMI) and water quality & safety analysis.
5. In **Circular economy** by means of advanced (opto-mechatronic) measuring techniques, which lead to increased performance of production processes (smart industry), and less waste (first time right design).
6. In **Mobility and transport** by developing technologies for automotive and aerospace metrology and communications, and low-latency networking technologies for autonomous mobility, as well as the future multi-terabit communication technologies based on optical infrastructure and -technology. From laser satellite communication to support the growing Internet of Things, to integrated photonic devices increasing the capacity needed and lowering the energy consumed in internet datacenters around the world.
7. In **Security and safety for society** by providing emerging photonic sensing and imaging technologies for higher levels of security and safety. Here the sophisticated surveillance 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”).
8. In **Innovative and inclusive society** by supporting access to the labour market and participation in society by providing new training opportunities with AR/VR and increasing connectivity through optical networks. For example optical infrastructure to enable ‘learn and work where you like’ and preventive (health) services on demand.
9. In **Digitization of industry** by making the Dutch industry more innovative, cost-competitive and resource-efficient with sensors, lasers, EUV lithography and 3D displays (Internet of Things, Smart Industry).

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[3] Europe’s age of light, Photonics21, November 2017

[4] Kennis- en Innovatieagenda 2018-2021, Maatschappelijke uitdagingen en sleuteltechnologieën, Topsectoren, dec 2017

And last, but not least, Photonics will lead to **new innovative entrepreneurship,** strengthening the **Human Capital Agenda**, resulting in captivating jobs for young people, photonics start-ups and new challenges for education at all levels, from primarily to high level education.

1.2 World-wide market for this roadmap, now and in 2020

The total world market for photonics in 2015 was estimated as 447 B€ [5], i.e. about 1/5th the size of the electronics market, which is significant when compared to other technology sectors and it is growing fast. From 2005-2015, the global market for photonics showed a real annual growth rate of 7% , which is twice as fast as the global GDP growth[6] and higher than in many other sectors (Food: 2%, Automotive: 3-5%). The European segment in the global photonics supply and demand equals 15%. The global sales growth from 2012 to 2016 for photonics components production equals a Compound Annual Growth Rate (CAGR) of 5.4%, and worldwide jobs growth equals 7% [7]. The expected world market for 2020 is 615 B€ [8].

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

According to the SPIE Industry Update 2018, the Netherlands is the 7th biggest producer of photonic components in the world. The Dutch companies active in photonics, e.g. Philips, OCE/Canon and ASML, rank 4th. The Netherlands also has an excellent position in the photonics research. Being ranked 6th in the global photonics research sector.[9] The strong academic tradition in the Netherlands in optics and photonics is the basis for the flourishing applied research in the Dutch high tech industry. For many years optics has been one of the core disciplines of leading industries such as Philips and ASML. Besides these multinationals, there are many very innovative Dutch SMEs active in the field.

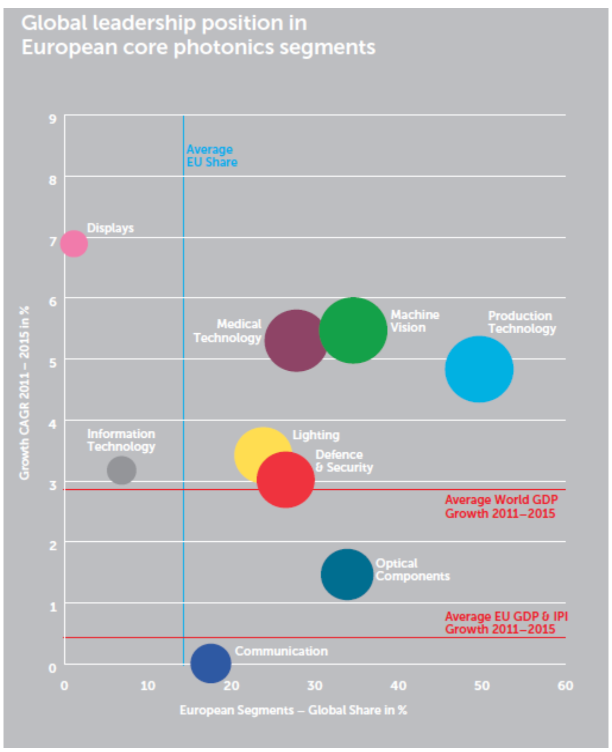

Figure 1 European share in global photonics, and growth rate [Europe's age of light, Photonics21, November 2017]

> "Lambert is worldwide market leader in camera based FLIM systems. Our Fluorescence Lifetime (FLIM) camera is being used in cancer research, and will be used to measure the efficacy of chemotherapy within a few days (vs >2 months now)." [Lambert Instruments]

According to the Optech study, the Dutch contribution is 4.4 B€ and this is currently dominated by production equipment (ASML), lighting (Philips) and printing (OCE/Canon). Medical

[5] Europe's age of light, Photonics21, November 2017
[6] Europe's age of light, Photonics21, November 2017
[7] SPIE Industry Update, S.G. Anderson, Febr 1, 2018
[8] Optech Consulting, Studie "Photonik 2013", in: Spectaris, VDMA, ZVEI, BBF, "Branchenreport Photonik 2013".

[9] http://spie.org/about-spie/press-room/pw15-news

systems and optical components/systems is estimated to be 0.5 B€. The Netherlands is market leading in the following sectors: production technology (in particular lithography), Solid State Lighting, OLED, Medical Technology with Imaging and diagnostics; Integrated Photonics; Optical Measurement, Machine Vision, CCD/CMOS-detectors; ICT: Printing and FttH equipment; Solar; Optical systems and components. Dutch SMEs target profitable niche segments in all photonic market sectors.

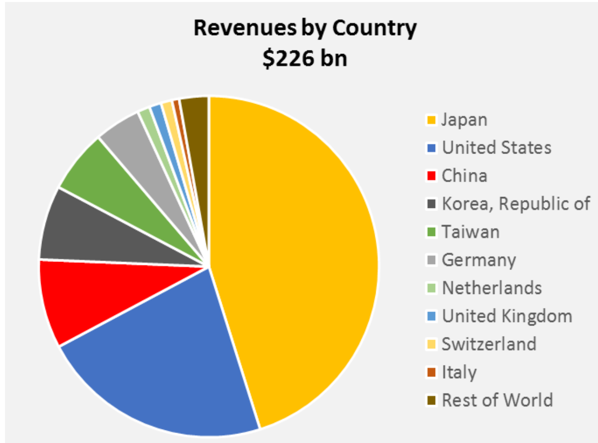

Figure 2 Geography of global production, 2016 (core photonic components and materials) Source: SPIE Industry Update 2018

Regional ecosystems

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 is studying medical photonics with a focus on the development of affordable minimally invasive screening methods to be able to make diagnoses very quickly and reliably.
- 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 NXP is located in this region.
- The Twente region has a strong knowledge domain with respect to the development and production of silicon nitride (TriPleX) technology based photonics integrated circuits, centered around Lionix International and the University of Twente. Further activities focus on optical sensing and detection (e.g. Sensata, PANalytical); medical diagnostics; optomechatronic systems (DEMCON); generic packaging technology (connected to the Fraunhofer Project Center @ UT) and the assembly of photonics and electronic circuits employing the state-of-the-art infrastructure of the Nanolab.
- The Brainport region has several photonics-based activities. The Eindhoven University of Technology (Institute for Photonic Integration), has a strong position in integrated photonic chips (e.g. on Indium Phosphide), and 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.
- 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.

For successful positioning within European and worldwide markets it will be beneficial to present the Netherlands as a single, coherent, and well-synchronized photonics region; this can be enabled by more collaborations, network meetings, building projects together to link the different parts of the photonics research, and additional budgets specifically for collaborations.

2 Application and technologies

Photonics is one of the most important key technologies for the 21st century enabling solutions for 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 for 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. The table below shows an overview of the technology groups and their contribution towards the different roadmaps and top sectors.

	Enabling oriented HTSM Roadmaps						**Application oriented HTSM Roadmaps**								**Application oriented top sectors/TKI's**						
	Advanced instrumentation	High Tech Materials	Embedded Systems	Nanotechnology	Components & Circuits	Semi Conductor Equipment	Printing	Lighting	Health Care	Security	Automotive	Aeronautics	Smart Industry	Space	Agro & Food	Water	Energy (TKI Solar)	Horticulture and source materials	Chemistry	Creative Industy	Life Sciences & Health
1 Photovoltaics					P										P		B				
2 Integrated photonics		P		P	P ★	P			P			P	P				P				P
3 Photonic detection	P					P			P	P	P	P	P	P	P	P		P		P	P
4 Photon generation technologies (lasers and light sources)	P					P ★	P	B ★	P				P	P							P
5 Optical materials (incl. thin films and coatings)		B	P	P		P		P					P	P			P		P		P
6 Optical sensors	P		P			B ★	P		P ★	P	P	P	P	B ★	P ★	P	P	P	P	P	B ★
7 Imaging technologies	P					P			B	P	P		P	P	P		P	P		P	B
8 Optomechatronics	P		P		P	P			P			P	P	P	P			P			P
9 Quantum (sensors and metrology)				P	P ★									P							
10 Optical fibers					B	P			P		P	P	P								P

Present Application (P) · Broad present application (B) · ★ Broad future application

Figure 2 Top 10 photonics technologies cross-overs with Dutch Top sectors and Roadmaps . (This is a preliminary outline, to be used as a starting point for discussion and further refinement!)

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:

- **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.
- **Photonic integration:** Includes the development of generic integration platforms and foundry models. Addressed technologies comprise III-V semiconductors e.g. InP, TriPleX and SOI, CMOS post processing; assembly, alignment and fixation, RF processing in optical domain (microwave 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).
- **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. Spatial light modulators are used to create wavefronts with programmable intensity and phase distribution.
- **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 spectroscopy), the measurement of displacement, stress or acoustic waves (e.g. with fiber-Bragg gratings) and 3D imaging systems for the automotive industry and for security applications.
- **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).
- **New methods and equipment for optics manufacturing:** includes injection molding, diamond turning, magneto-rheological finishing, and robot polishing.

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

"Optical imaging is the most important imaging modality in Health care. In fact,. Without Optics and photonics, Health care would not exist. Optics in the medical imaging market is larger than for the well-known radiological imaging applications." [UVA-AMC]

"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]

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

- **New materials:** Includes semiconductors, glasses, plasmonic materials, metamaterials, photonic crystals, nano- (plasmonic) structures, quantum dots, nano-crystals, 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, in extreme environmental conditions, and in combination with other key enabling technologies such as microelectronics.

- **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), CMOS and other single photon technologies, quantum cascade lasers, VCSELs, 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 and new scintillation materials.
- **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.
- **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, single photon and plasmon detectors.
- **Applications of displays**: applications of displays combined with sensors in Virtual Reality and Augmented Reality

”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]
“Open access to the Dutch and German foundry platforms is organized by the European JePPIX organization, which is hosted by TU Eindhoven. Photon Delta is organizing the eco-system around these facilities for development and manufacturing of Photonic ICs.” [TU Eindhoven]
Knowhow position: world-leaders in measurement of polarization and design of diffractive optical elements, well-known experts in wave-front control. [Leiden University]
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]
“The development of new tools for large area, noninvasive nanoparticle detection and contamination detection at the nanometer level is of extreme importance for nanofabrication, detection and visualization of biological nanoparticles for studying 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]

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).

SC 1: Energy and CO2

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 .

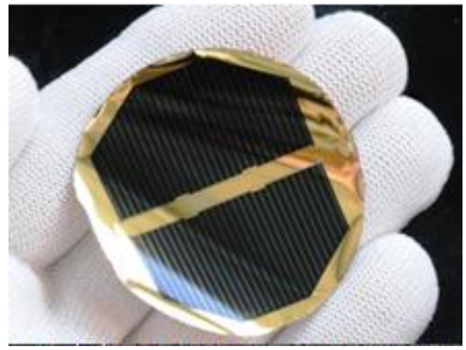

Figure 3 *Development of novel photovoltaics, based on ultra-high efficiency thin-film III-V cells or on organic materials. [Radboud University]*

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 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.

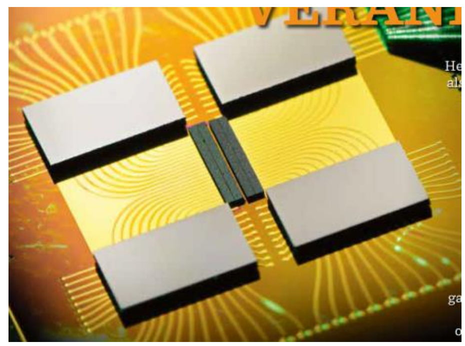

Figure 4 Massive Parallel Interconnect [University o*f Eindhoven]*

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]

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. Furthermore, the power consumption of data centers and networks can be decreased by employing energy saving photonics in data interconnects, transmission and switches.

“Energy is growing in importance – it relies on tighter integration of light and materials research” [AMOLF]

SC 2: Agro-Food

The world population is increasing rapidly. The United Nations projects that the population will grow from 7.6 billion people in 2017 to 8.6 billion in 2030 and 9.8 billion in 2050.[10] All these population have to be fed. 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 the pressure for more sustainable agro and food production processes.

Figure 5 Photonics for precision farming (source: Avantes BV)

> "The societal challenge for Agro 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]

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

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

Photonic sensors (using Near-Infrared (NIR) spectroscopy) also monitor the **quality of food** for food safety purposes, for example of packed nutrition, fruit and crops before and during harvesting and in the shop. Another example is 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.

SC 3: Healthcare

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 a constant pressure for the healthcare system.

Figure 6 Philips Digital Pathology

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[10] United Nations (2017). World Population Prospects: The 2017 Revision

Therefore, it becomes more important to prevent diseases instead of treating them. The 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 treatment makes point-of-care diagnostics and better critical care possible. Miniaturization of the medical devices can bring healthcare from the clinic towards the practitioner/patient and even further directly to patient home. Bringing the best possible healthcare to the patient is important, non-invasive diagnostics and surgery is therefore one of the biggest challenges. 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 more healthy lifestyle. Exposome is a new trend in this field, where through knowledge of the lifelong exposure health could be predicted.

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).

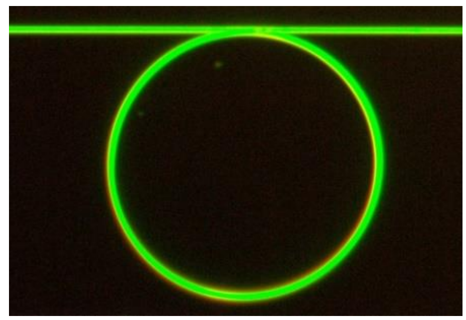


Figure 7 Rare-earth doped Al2O3 ring to make "active" biosensors with increased sensitivity. Source: University of Twente

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

Photonics components are part of most of the 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, 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 the future R&D in photonics.

"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]

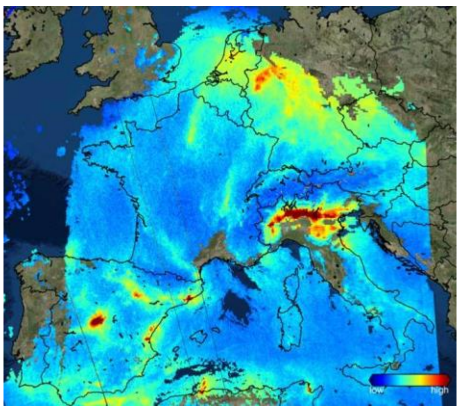
Advanced (medical) photonics also offers non-invasive monitoring, for example through skin with light – spectroscopy, and minimal invasive surgery using fiber probes. Optical instruments are developed for super-resolution, long-time live-cell imaging, and full organoid imaging for developing and studying 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.

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]

SC 4: Climate and water

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.

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 & 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. Other optical sensors detect air pollution in cities. Further examples are photonic sensors for water quality control in distribution networks and reuse facilities and 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-impuls to the NWA route “meten & detecteren”. In this route metrology for both climate and health technologies will be developed.



Figuur 1 TROPOMI First results [TNO]

“State-of-the-art technologies: Self-aligning freeforms, and spectral imaging with compact instruments.” [cosine]

Figure 9 Measurement of net radiation to estimate regional evaporation of water [Hukseflux Thermal Sensors]

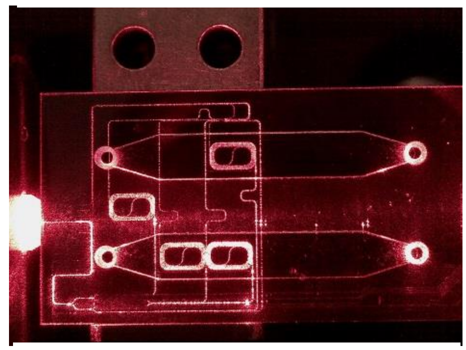


Figure 8. Waveguide based Surface enhanced Raman spectroscopy (i.e., waveguide SERS) is being developed for the detection of pollutants in drinking water. *[*University of Twente*]“*

“Nano.article detection for instance, is optical detection and visualization of nanoparticles for studying weakly scatters such as air pollution in urban cities, due to ultrafine dust. This is also very challenging due to the small particle sizes (10-100 nm) and the consequences it has to human health.”

SC 5: Circular Economy

To change the worldwide trend of extensive use of raw materials and thus exhaustion of ‘earth commodities’ or 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.

Photonics contributes to the circular economy by means of advanced (opto-mechatronic) measuring techniques, leading to increased performance of production processes (smart industry) and reduction of waste. The development of sustainable technologies such as future developments in solar energy benefit from improved measurement and analysis technologies based on photonic components.

Furthermore, it leads to precision instruments assisting the development and producing products ‘first time right’, as well as to develop inherently reusable products. Furthermore, photonics provide novel and more insights in growth conditions in agriculture, helping the reduction of nutrients needed and therefore lowering the footprint.

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

> “Devices to monitor food quality and safety during the continuous food chain. From Feed, to Farm to Fork..” [Ocean Optics]

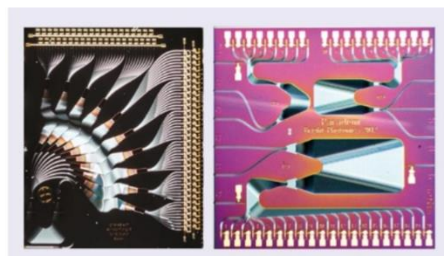


Figure 10 Readout system for fiber optic sensors [Jeppix]

SC 6: Mobility and transport

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

For the automotive industry, with a focus on intelligent electromechanical systems, a photonics based sensor technology can be integrated in the form of light-based detection and ranging (LIDAR) and mechanical parts requiring robust components for in-car communications, monitoring, warning and vision.

Next fifth generation (5G) mobile wireless photonics can 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.

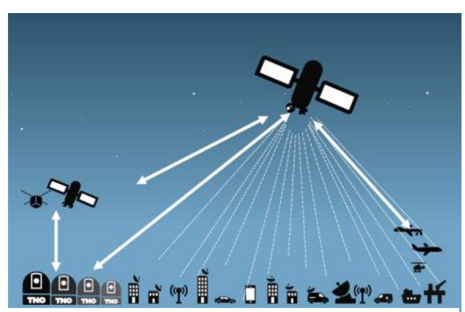


Figure 11 Laser Satellite Communication [TNO]

In aerospace, examples of photonic systems are new optical equipment using e.g. 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 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]

SC 7: Safety and Security for Society

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 consuming 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.

> "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.

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

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.

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

SC 8: Innovative and inclusive society

Technological development changes the world rapidly and has high socio-economic consequences. Jobs disappear or change and new skills are required due to automation, robotization and digitization, both at work and for daily life activities. Social participation of individuals in the society and in the labour market becomes a challenge.

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.

Figure 12 *Augmented Reality [*TNO*]*

Connectivity within homes and the connection from homes to the outside world depends on high-speed communication between 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]

SC 9: Digitization of industry

The Dutch industry is an important player in dealing with societal challenges. 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.

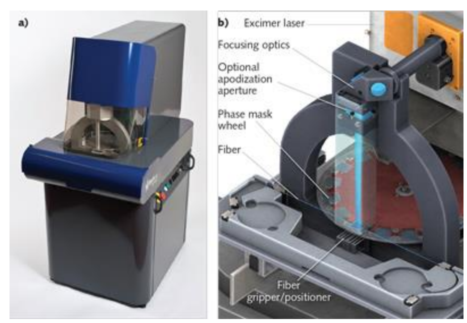


Figure 13 NORIA tool, developed by Hittech based on TNO technology, enables Somni to produce Fiber Bragg Grating based sensors for medical and industrial applications.

Photonics is a vital enabling technology for "Industry 4.0" or "Smart Industry". 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.

Extreme ultraviolet (EUV) lithography systems offer solutions for decreased the technology node in the semiconductor industry. And photonic integrated circuits make mass-manufacturable photonic solutions possible.[11]

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

- High-power lasers for industrial processing
- Fiber optics as the backbone and neural system of the Industrial Internet.
- Use op 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 will drive artificial intelligence and smart robotics
- The industrial production of micro and nanomaterials and structures is another rapidly evolving spin-off of 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.

"We are one of the European leaders in fiber-to-the-home gateways.." [Genexis]
"SMILE2: Smart Multilayer Interactive Optics for Lithography at Extreme UV Wavelengths [University of Twente]
"More technological advances will make it possible to place audiences in the middle of the action and to offer them Immediacy, Individualization, Interaction and Immersion..." [Grass Valley]

2.3 Questions and milestones in this roadmap until 2025

The European platform Photonics21 has presented a comprehensive overview [12] of "the way forward": the implementation of the new vision for Photonics. General issues such as establishing standards and regulatory frameworks have to be realized on European level. Some specific questions and milestones forming 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 CO2: The government and regulatory bodies play a large part in the development of energy and CO2 related technology, through CO2 pricing, standards for compliance verification and new regulations to force the reduction of CO2 output. Simultaneously the public sector plays an important role in promoting and implementing energy saving technology e.g. in lighting.
- Agro and Food: Spread technology via involvement and education of farmers, and support technology uptake by smaller farms.
- In Healthcare: Open up the healthcare market to new technologies, and improve access to healthcare markets for innovative SMEs.
- In Circular Economy: Focus innovation on sectors that will ultimately contribute the most at the least net cost.

[11] Europe's age of light, Photonics21, November 2017
[12] Europe's age of light, Photonics21, November 2017

- Innovative and inclusive (and digital) society: Strengthen the Smart Industry ecosystem, support a powerful and secure telecommunications infrastructure and facilitate pilot production lines.

Developing a Dutch vision on the future

This photonics roadmap is not complete without a 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.

A (very preliminary) shortlist of the main application fields of photonics and relevant areas of research and technology development is given here:

- 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; metrology and imaging systems for semicon industry, and Smart Industry
- Photonics for Energy and climate: more energy efficient photovoltaics, climate monitoring by remote sensing, efficient lighting.
- Photonics for Agro and food: 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. A joint effort of all players in the Dutch photonics field is required and crucial in the near future, with support from national and regional government.

3 Priorities and implementation

The Netherlands is very strong in research in the technologies which underpin photonics, but 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:

"We have strong technology that we should bring to applications….. And we must further strengthen the bonds between academic and industrial research so that we have even stronger technology tomorrow". [University of Utrecht]
"The applications with which we touch, are almost exclusively in developing systems for metrology, analysis and inspection, like photonics miniaturization in healthcare, and optical metrology in agro.[Laser 2000]
"2017 started the pilot for our new educational track on opto-mechatronics and micro-optics within the Mechanical Engineering Master curriculum.." [TU Delft]

- Photonics research and development must centre around realizing novel techniques and devices that can contribute to the societal themes. This requires close cooperation between knowledge institutes and Dutch business innovators, delivering technology solutions to address key societal themes and generate new innovative entrepreneurship.
- 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 work-force and providing access to state-of-the-art manufacturing technologies.
- Creating regional Digital Innovation Hubs, 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 big data processing.
- Innovations are required in assembly technologies to enable competitive advantage with respect to low-wage economies. Photonics markets differ from electronics markets in that they are high value with comparably low volume, and this has driven significant assembly work to low-wage economies. A 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.

Figure 14 Dual-channel VIS-NIR spectrometer (350nm – 950nm), 1 cc including electronics. [Anteryon]

- Recent events such as answering parliamentary questions about photonics by the Minister of Economic Affairs (21 August 2017) and the subsequent addition of the subject Photonics to the spearheads of the new government, support the importance of Photonics in the Netherlands. The next steps are the update of the HTSM Photonics Roadmap in this document and the development of a **National Masterplan Photonics**. Recently several new initiatives (on both national and regional level) have been set up by the clusters Dutch Optics Centre (DOC), Photon Delta, and PhotonicsNL. Photonics are now acknowledged to have a priority status on a national level (ministry of Economic Affairs and Climate) and regional level (provinces) 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. Additional funding from existing and new means have been established and will increase in the near future, according to the Government plans ("Regeerakkoord").

- During 2016 and 2019 follow up programs in Topconsortium Kennis & Innovation (TKI's) will be initiated based on the roadmap. The PhotonicsNL association will give support with setting up, and maintaining the Photonics roadmap. The Memphis consortium has coordinated and initiate new collaborative projects.
- 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 programs Horizon2020 and ECSEL with their specific photonic calls and increased budget. Applied 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 technical 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.

We also propose the development of a set of Key Performance Indicators (KPIs) for both social and industrial valorisation, which quantify the amount of licensing, utilized knowledge transfers and start-ups and thus provides an instrument for managing resources to successful PTCs.

3.1 Implementation 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 and OCE/Canon, TE Connectivity 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.

Photonics NL: The Dutch portal for optics and photonics professionals PhotonicsNL is the unique society for Photonics in the Netherlands. Photonics is being recognized worldwide as a key enabling technology for the 21st century and especially in Europe by the European Commission but also in the Netherlands by the High Tech Top sector. Our mission is to stimulate photonics innovation by enabling collaborations and cross-fertilization between companies and industries, to increase the level of awareness of the importance of photonics for our economy and to increase the knowledge of photonics at all levels of education.

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 utilisation 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.

The **Photon Delta** initiative was launched from Eindhoven brings industry and universities together to foster the Photonic Integration technology into new and emerging markets. In cooperation with Twente, Nijmegen and Delft, this initiative aligns Dutch efforts in photonic chip technology, enabling the Netherlands to punch above its weight. The focus is to bring photonic chip technology developed in the Netherlands into an industrial ecosystem of companies able to address markets across the full scope of societal challenges, developing the necessary skills for design, processing, packaging and commercialization. This **Photonic Integration Technology Center** provides the focal point, leveraging the international reputations for Dutch researchers in integrated photonics, and enabling the Netherlands to become a hotspot for Photonic Integration. The initiative is supported by Dutch and European industry players, the universities, and regional governments. Photon Delta is also a key-enabling technology-related Digital Innovation Hub covering Europe and operating from a base in the South-Netherlands region. Since September 2017, we have been one of the two lead regions in the establishment of the European Photonics Alliance.

Recently these three cluster organizations joined forces, with 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.

ARCNL is a public-private partnership between VU, UvA, NWO and ASML. They perform fundamental research with a strong application perspective. 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.

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.

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 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 by joining expertises, while continuing to foster new research and to develop new expertises. The research infrastructure and cleanroom facilities of the MESA+ Nanolab play a pivotal role in this.

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 instruments that stimulate innovation

The results of the current SmartMix-Memphis project, IOP-Photonic Devices projects, 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 opportunities of photonics in general and the benefits of generic foundry-based technologies are addressed in three major national R&D-programs: IOP Photonic Devices, STW Perspectief “Memphis” and NWO-TTW’s “Generic Technology for Integrated Photonics” and “Smart Optical Systems” which initiated successful collaborative consortia between industry and universities and have put the Netherlands at the forefront of Photonics technology development. The JePPIX organization assists users around the globe to get access to advanced fabrication facilities for Photonic Integrated Circuits. JePPIX has published its 2015 roadmap[13].

NWO has granted and supported the past years various IPP programmes (via Perspectief Programs of TTW (former STW) and via IPP programmes of NWO-Science and NWO-Institutes (former FOM):

[13] The road to a multi-billion Euro market in Integrated Photonics, JePPIX ROADMAP 2015

- **MemphisII** Merging Electronics and Micro & nano Photonics in Integrated Systems programme with 7 university research groups and 20 industrial partners (budget 6 M€ and industry contribution of 2.6 M€ in cash+in kind).
- **Cancer ID** with 7 academic research groups and 22 industrial partners (budget 4,7 M€ and industry contribution of 1.7 M€ in cash+in kind).
- **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.
- **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).

In addition, several HTSM projects and NWO projects with academic and industrial partnering have been granted and are currently running.

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

Photonics is defined by the European Commission as a Key Enabling Technology since 2009. Photonics has a high research priority for the EC and is well represented in the calls for proposals. The European Commission has funded 67 Photonics Horizon 2020 Projects up to the year 2017, which is approximately 380 M€. Furthermore, Photonics21 identified a number of outstanding PPP calls for 2018-2020 as relevant for Photonics. Excluding the European Innovation Counsel programs these projects add up to approximately 1040 M€ in 2018 and 950 M€ in 2019.

Our mission.
European leadership in photonics will deliver these benefits by 2030:
- Instant diagnosis of major diseases
- Quality food from farm to fork
- Accident- and congestion-free road transport
- A truly circular economy
- A million new jobs In 2030
- 10% higher productivity
- Zero downtime in a terabit economy
- Photonics as a flagship science for innovation

[Photonics 21]

The Dutch photonics community is very active and successful in H2020 program, in projects supported by research and development in large companies (e.g. Philips and ASML), Dutch SME's and research institutes such as TNO, ASTRON, NOVA, SRON and VSL. These R&D efforts will be continued and many more projects are foreseen in the next years.

The Netherlands is involved in a few cross-national projects with Dutch partners such as:

- EU-PENTA project "ESAIRQ" on gas sensing (2018-2020)
- ICT-29-2016: Photonics KET 2016
    - RIA: Application driven core photonic technology
    - iii. Pervasive high-specificity and high-sensitivity sensing for a safer environment
- FLAIR: Flying ultrA-broadband single-shot InfraRed Sensor
- Real-time "interactive storage" quality control in fresh agro products (QCAP)

- InSPECT (H2020) on miniaturization of dedicated spectrometer instruments
- ASTONISH (ECSEL) on hyperspectral imaging for tissue discrimination
- InForMed (ECSEL), POSITION-II (ECSEL) on optical sensing inside medical catheters
- Ecsel projects (Panorama, Bastion, Exist)
- MSCA xCLASS
- EIT Raw-Materials REGENERATION project
- EPRISE-project: Empowering Photonics through Regional Innovation Strategies, for Medical Technologies, Pharmaceuticals, Agriculture and Food
- Eurostars OCTIC; medical
- ADOPSYS : EU project on new optical design methods
- ACTPHAST: EU project to support SME with their optics and integrated photonics product development in order to increase the economic potential of these companies
- MOON: EU funded project on Multi-modal Optical Diagnostics for Ocular and Neurodegenerative Disease (TNO)
- Interreg Vlaanderen-Nederland: Flexlines (flexible imagers)

Until now, the European Commission has launched four pilot lines. Eleven companies from The Netherlands participate in these pilot lines. These pilot lines cover different application areas, ranging from health applications (PPP Project PIX4Life), flexible organic light-emitting diodes (PPP Project PI-SCALE), sensors for the detection of chemicals in gas and liquids (PPP Project MIRPHAB to Photonics Integrated Circuits (PPP Project PIXAPP).[14]

[14] Photonics21 (2017). PPP Impact Report 2017.

4 Partners and process

4.1 Names of engaged partners from industry, science, and public authorities

Over 200 Dutch industrial and scientific partners, active in Photonics, have been requested to provide input to this roadmap. Within a few weeks input was provided by a group of about 40 photonics colleagues :

Eric de Leeuw (Diamond Kimberlit), Benno Oderkerk (Avantes), Martin vd Mark/ Jean Schleipen (Philips), Klaas Jan Damstra (Grass Valley), Kees van den Bos (Hukseflux), Oded Raz (TU/e - IPI), Jan Boers (Dino-Lite), Silvania Pereira (TU Delft), Stefan Bäumer (TNO), Pieter Kramer (Laser 2000), Gerlas van de Hoven (Genexis), Femius Koenderink (AMOLF), Hans Naus (Camlin Technologies), Stefan Witte (ARCNL), Andrea Fiore (TU/e), Frans Harren (Radboud University), Jeroen Wehmeijer (Lambert Instruments), Pepijn Pinkse (UTwente), Sonia Garcia Blanco (UTwente), Willem Hoving (Anteryon), Theo Rasing (Radboud University), Urs Staufer (TUD), Christoph Keller (Leiden University), Kevin Williams (TU/e), Guus Taminiau (PhotonicsNL), Ton van Leeuwen (UVA AMC), Paul Urbach (TUD), Erik Ham (DOC), Babette Bakker (TNO), Allard Mosk (Utrecht Uni), Huub Salemink (Radboud / TUD), Marnix Tas (Sioux CCM), Marco Beijersbergen (cosine), Egbert-Jan Sol (Smart Industry), Hugo de Haan (Innophysics.nl), Michel Verhaegen (TUD), Maria Sovago (NWO), Remco Nieuwland (SOMNI), Marco Snikkers (Ocean Optics)

4.2 Process followed in creating/maintaining this roadmap, including 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. This 2015 version builds 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[15]. Invitations for input were sent out to more than 200 contact persons at knowledge institutes and industry; the partners that sent their input are listed in section 4.1 . Their feedback, including quotes and pictures, is included in this version.
The editing of the roadmap is coordinated by PhotonicsNL - Bart Snijders, with inputs and comments from Bart Verbeek, Maria Sovago (NWO) and many others, and in collaboration with the roadmap responsible Hans van den Vlekkert (LioniX International). A set of recent Dutch, European and global documents on Photonics has been used as reference (see footnotes).

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[15] Kennis- en Innovatieagenda 2018-2021, Maatschappelijke uitdagingen en sleuteltechnologieën, Topsectoren, dec 2017

5 Investments

Public-private partnership R&D budgets

The following tables indicate the public-private partnership R&D investments according to the best estimates currently available.

Note: The budgets for 2019, and beyond, still need to be updated.

Tabel 1

Roadmap k€	**2015**	**2016**	**2017**	**2018**	**2019**
Industry [1]	4.700	3.550	3.100	11.200	10.500
TNO [2]	4.000	4.250	4.250	4.100	4.300
NLR					
NWO	4.600	3.800	3.800	5.500 [3]	1.500+ [4]
Universities	5.300	5.000	4.250	4.100	4.100
Dept./Regions	175	175	750	750	750
Grand Total	18.775	16.775	16.150	22.950	21.150

Tabel 2

European agenda within Roadmap k€	**2015**	**2016**	**2017**	**2018**	**2019**
Industry	1.000	900	750	650	600
TNO	100	175	250	325	350
NLR					
NWO					
Universities	5.000	4.500	4.000	3.500	3.700
Co-financing of European programs	175	175	750	750	750
EU Commission	175	175	750	750	750

Notes

1) Increased numbers for 2018 and 2019 is based on expected industrial collaboration with NOVA.
2) TNO numbers are exclusive Semicon and Space.
3) Recently updated (Jan 2018)
4) New projects have not been included yet