2023

Photonics Roadmap

HTSM Roadmap Photonics 2023-2030.
By PhotonicsNL, Optics Netherlands, PhotonDelta, NWO, RVO and partners.

Executive Summary

Since 2018, the Photonics Roadmap has been closely aligned with the Societal Challenges outlined by the Dutch Top Sectors. Over the past few years, the global and Netherlands Photonics ecosystems have seen significant advancements and have been instrumental in addressing key challenges. This Roadmap provides an overview of these developments and highlights the strategic directions for the future.

The National Agenda of Photonics has been essential in strengthening Dutch initiatives focusing on Optics, Photonics, and Integrated Photonics. Additionally, the optics ecosystem has expanded through the collaborative efforts of PhotonicsNL, PhotonDelta, and Optics Netherlands. This collaborative approach has accelerated progress and innovation in the ecosystem for (integrated-) photonics and optics.

Photonics and optical technologies have been rightfully recognized as a Key Enabling Technology (KET). This recognition extends to multiple application areas, including Quantum Technologies and Artificial Intelligence. This acknowledgment enhances the role of photonics in driving innovation across various market segments.

The Dutch Photonics Ecosystem has seen a significant increase in international engagement, resulting in enhanced trade, research, innovation, and collaboration with partners worldwide, particularly in the EU, Asia, and the Americas. This global outreach strengthens the Netherlands' position in the photonics sector. The Netherlands boasts a thriving ecosystem of over 300 companies that rely on optical technologies in their core operations.

Furthermore, the financial sector has shown a growing interest in photonics, resulting in significant investment rounds. A major milestone was achieved with the award of the National Growth Fund grant, of 472 M€ for the years 2023-2029. With a combined effort from industrial partners, the substantial investment will amount to approximately 1 B€ to support research, innovation, human capital development, and industrialization within the Dutch Integrated Photonics ecosystem. This not only amplified initial capital but also increased confidence in the production capabilities of front- and back-end foundries, a key element of the Growth Fund program. The launch of "photon ventures" in 2023 further underscores the attractiveness of the Integrated Photonics business.

This updated Photonics Roadmap offers a more comprehensive perspective on how Optics, Photonics, and Integrated Photonics play a vital role in addressing Societal Challenges. While this roadmap primarily focuses on the Dutch Ecosystem, it recognizes that translating research into successful businesses is essential for tackling societal challenges through valorization efforts by recognizing the immense potential of the Photonics ecosystem and creating a significant opportunity to facilitate the growth of groundbreaking companies. This can be further enhanced by ensuring that the entire value chain, spanning from fundamental research and development to large-scale production, is firmly rooted within the Netherlands. Such a comprehensive approach will drive innovation, economic growth, and progress in addressing societal challenges.

In conclusion, the Photonics Roadmap presents a clear trajectory for the future, building on past achievements and strategic collaborations. It positions Photonics and optical technologies as a key driver in addressing Societal Challenges while capitalizing on the vibrant ecosystem, ultimately contributing to the prosperity and well-being of the Netherlands and the broader global community.

Content

Introduction

Since 2018 the Photonics Roadmap has been based on the Societal Challenges as described by the Dutch Top Sectors. The global Photonics ecosystem as well as the Netherlands Photonics ecosystem have undergone important developments since the publication of the last HTSM Roadmap of Photonics. Through cooperation at the (inter)national level important steps have been made. This included among others the following activities:

1. The creation of *The National Agenda of Photonics,* a higher TRL level initiative for Optics, Photonics, and Integrated Photonics, and the further clustering of the optics community through PhotonicsNL, PhotonDelta, and Optics Netherlands.
2. The recognition of Photonics as a *Key Enabling Technology* (KET), with multiple application areas and technologies, for example, Quantum Technologies and Artificial Intelligence, has been achieved.
3. Increased trade, research, innovation, and collaboration of the *Dutch Photonics Ecosystem* with international partners worldwide especially in the EU, Asia, and the Americas.
4. Most recently, the award of the *National Growth Fund* grant with a total budget of 1.1 B€ for the years 2023-2029 for research, innovation, Human Capital, and industrialization of the Dutch ecosystem for integrated Photonics.

Photonics as a key enabling technology is recognized and embedded in the Agenda key enabling technologies 2020-2023, and various *Multi-Year Programs* (MJPs). 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 the Topsector High Tech Systems and Materials (HTSM). Key-enabling technologies like Photonics and optical technologies are also the backbone for the new national technology policy with a 'National Technology Strategy'.

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

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

Compared to the previous Roadmap 2018-2023, this updated Roadmap offers a more comprehensive perspective on how Photonics plays a crucial role in addressing Societal Challenges. This is achieved by exploring its interconnections with other technologies and applications. While primarily concentrating on the Dutch Research Agenda, this Roadmap acknowledges that translating research into business ventures is a vital component in tackling the societal challenges that are being highlighted through valorization efforts.

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

1. Societal challenges and economic relevance

Photonics, a key enabling technology that uses the properties of light, finds itself at the forefront of a diverse array of applications. Its significance in bolstering and facilitating an array of services and products is on a continuous ascent. As humanity strives to meet the ever-expanding demands in communication, enhancing quality of life, and safeguarding health, the overarching goal is to achieve these milestones with the least possible ecological footprint stemming from these technological advancements. Within the Netherlands, the Photonics ecosystem thrives, boasting over 300 enterprises and institutions, where a multitude of individuals are engaged in the field of Photonics, either directly or indirectly. This dynamic workforce spans major corporations, small and medium-sized enterprises (SMEs), and innovative start-ups across various industries.

Photonics plays a crucial role in addressing a wide range of societal challenges by leveraging the properties of light for various applications. There are several ways in which Photonics contributes to tackling these challenges. Photonics is a versatile technology that directly addresses numerous societal challenges by advancing fields such as healthcare, energy, communication, and environmental monitoring. Its applications contribute to improving the quality of life, reducing environmental impact, and driving technological innovation across various sectors. This roadmap is based on several foundational principles as listed below.

- **Significance in Addressing Societal Challenges**: Photonics presently plays a significant role in resolving critical contemporary societal issues.
- **Amplifying Research and Innovation Yield**: Our focus encompasses valorizing a substantial portion of scientific knowledge and infrastructure, aiming to maximize the returns from research efforts and joint innovation.
- **Nurturing Human Capital**: Cultivating a highly educated populace is pivotal in realizing our aspirations, whether directed towards pioneering research or the social and economic application of knowledge.
- **Collaborative Endeavor Involving Science, Government, and Enterprises**: The responsibility for driving this process lies jointly with the scientific community, government bodies, and corporate entities.
- **Enhancing Excellence**: The Netherlands holds an international lead in various Photonics research domains. Preserving and, when feasible, augmenting this position is imperative. It's essential to also navigate the space between fundamental science and practical applications, preventing a potential hindrance to innovation.

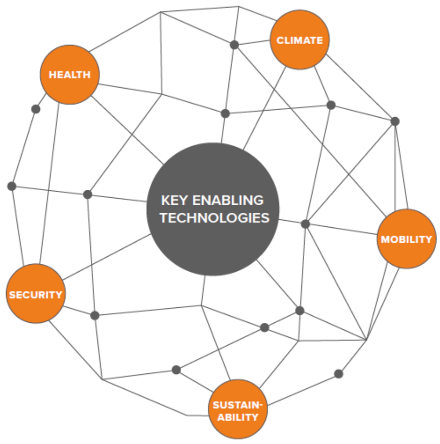
1.1 Societal challenges addressed in this roadmap

Photonics is the technology of light (photon/wave) generation, propagation, modulation, signal processing, switching, amplification, detection, and sensing. The Netherlands has a great history in the field of Optics and Photonics and to this day, the Dutch scientists and engineers are still pioneers in researching and developing new technology in the field of Photonics.

Offering unmatched speeds and energy efficiencies, Photonics has been termed a Key Enabling Technology (KET) and as such allows for the creation of 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

Slowing and mitigating climate change is 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.



To reduce the emission of greenhouse gasses, more energy-efficient photonic solutions are being developed. This includes very efficient light sources, (O)LEDs, micro LEDs, energy generation by highly efficient solar cells, and more energy efficient data centers by application of photonic ICs. Innovative optical technologies are being developed that convert sunlight directly into hydrogen or syngasses contributing to reducing the greenhouse gas effects. Photonics is also used to study climate change by providing advanced detection technologies, such as earth observation using advanced optical pollution detection instruments (such as TROPOMI) and water quality & air safety analysis.

2. Sustainability and Circularity

The world population is increasing rapidly. The United Nations projects that the population will grow from 7.9 billion people in 2022 to 8.5 billion in 2030 and 9.7 billion in 2050. There is a need to ensure we can sustainably feed 10 Billion people by then.

Not only does the demand increase, but the demand also changes. More people can afford more nutritious products. More consumers choose healthy food, as a response to a growing share of people with healthcare problems, such as obesity. This is all happening in an environment where climate change accelerates and so does the pressure for more sustainable AgriFood production processes with reduced emissions of greenhouse gasses.

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

3. Health

To increase the quality of life for a growing aging population the use of 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 and remote diagnostics all leading to improved monitoring of the evolution of diseases.

4. Safety and Security

With photonic sensing and imaging technologies we can provide higher levels of security and safety. Sophisticated surveillance, authentication, and encryption technologies are used in the communication field as well as in logistics. Examples are nano-dust detection, terahertz imaging technology, and secure key and information exchange in a "quantum internet". In the current global environment, photonic technologies play an increasing role in defense as well.

5. Mobility

Smart and green mobility needs the development of various technologies. Photonics is crucial regarding autonomous mobility (e.g. LiDAR) and the abundance of sensory data being created by terrestrial and airborne platforms (including satellites) requires low-latency and multi Terabits/sec network capacities.

6. Communication

Data consumption is growing exponentially on a global scale. This drives the need for ever-faster switches and systems in data centers, doubling every 2 years. Moreover, the energy consumption is becoming untenable both from a cooling point of view and from the overall energy consumption which spans end-users, data centers, data transmissions, and telecom networks in the Netherlands. The recent growth in Artificial Intelligence applications is resulting in further energy consumption. (Integrated) Photonics is a major contributor to possible solutions for these challenges. In telecom, we see comparable trends with mobile data use surging with 6G and beyond coming up in the next 5-10 years.

7. Photonics and Optical Technologies Report 'Herijking sleuteltechnologieën 2023'

Key enabling technology and application	Definition
Photovoltaics	Photovoltaics is the technology in which sunlight is converted into electricity using solar cells.
Optical systems and Integrated Photonics	Optical systems are systems constructed to refract or reflect light to perform certain optical functions. For example, communication is possible with photons as an information carrier. Integrated Photonics is the technology that integrates various photonic functions (generating, modulating, detecting, etc.) in a functional photonic chip. System integration is an important element in the application of Integrated Photonics.
Photonic/optical detection and processing	Photonic/optical detection and processing involves capturing and measuring photons and other light waves across the full frequency spectrum (including X-ray and UV) received from images, data links, and experimental spectroscopic investigations, among others. Photonic sensing deals with the design, manufacture, and testing of single and multiple detectors. This also includes measuring, designing, creating, simulating, and testing optical systems.
Photon generation technologies	Photon generation technologies involve the generation of photons using lasers and other light sources. The emphasis is increasingly on single photon generation, which is important in quantum technology, high-power lasers for industrial processing, and fiber lasers for ultra-short pulses.

1.2 World-wide market of Photonics by 2030

According to a recent European Investment Bank (EIB) study the global Photonics market is truly enormous with a market size of 652 B€ in 2019. Europe represents 103 B€ of the total, where it should be understood that this market represents a wide variety of application areas with correlating products, services, and value chains. This includes, but is not limited to, lenses, instruments, lithographic scanners, displays, and PV, to name a few. The economic impact of Photonics within the Netherlands is large and its growth rate of 7%, is significantly higher than the average GDP growth rate.

During the transition towards digitization, it is clear that photonic 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 second place in the world's market, just behind the USA, and well ahead of China. The collective efforts of government, science, and industry and the successful networking across Europe are an important part of this.

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

1.3 Competitive position of the NL ecosystem

Photonics is a fast-growing technology and therefore an important driver of employment and economic growth in the Netherlands.

Since the publication of the National Agenda of Photonics in 2018 the impact of Photonics as key enabling technology has been growing steadily. More than 300 companies with their headquarters in the Netherlands contribute 30 B€ of revenue to the economy with an annual expected job growth of 5-20 percent.

The high growth expectations are reflected in the initiatives taken at the regional level. Several provinces collaborate to build on their strength in the field of Integrated Photonics aiming for thousands of new jobs in the future, see CITC and PITC. The leverage Photonics offers to the manufacturing industry and end markets is considerable.

1.4 Regional focus based on (inter)national collaboration

The expertise required for Photonics in the Netherlands is concentrated in multiple locations, working on a variety of topics. For successful positioning within European and worldwide markets, we present the Netherlands as a single, coherent, and well-synchronized Photonics region. However, while the Dutch Photonics ecosystem has these strengths, global competition remains intense. Other countries and regions also have vibrant Photonics ecosystems and are investing in research, development, and commercialization. Staying competitive requires continuous innovation, investment, and adaptation to emerging trends through collaborations, network meetings, and events, specifically for collaborations. Below are 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 to 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. In Amsterdam, these are important 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 the growth of the Photonics industry.

- The Twente region, with the University of Twente and the MESA+ Nanolab, has a strong knowledge base concerning 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-ups through direct participation by supplying capital, IP, and facility sharing with innovative start-ups such as PHIX Photonics Assembly for assembly and packaging of Integrated Photonics and QuiX Quantum for commercializing photonic-based quantum technologies. As part of the PhotonDelta growth fund large investments in R&D as well as an upgrade of the MESA+ facilities and a dedicated foundry (New Origins) are planned.

- The North Brabant region has various Photonics-based activities. They have a strong position in integrated photonic chips based on Indium Phosphide, in related materials, and communication systems. The region also builds actively on the developments needed for production and the back-end processes to bring these technologies to the market. Equipment manufacturing, including the required Photonics technologies, is also strong in this region, for photovoltaic, microelectronics, and healthcare applications. Photonic technologies for consumer electronics and lighting are also developed by many organizations. ASML is an innovation leader in semiconductor manufacturing equipment. ASML develops lithographic scanners (with extreme ultraviolet (EUV) and deep ultraviolet (DUV) light), metrology, and computational lithography tools with partners from industry and academia throughout the Netherlands (TNO, ARCNL, TU Eindhoven, TU Delft, University of Twente). Also here as part of the PhotonDelta Growth Fund, large investments in R&D, start-ups, and InP industrialization are being planned.

- In 2022 PITC started as an integrated Photonics development center. It is a cooperation between TNO and the universities of Twente and Eindhoven and is active in both regions.

- The South Holland region contains a unique optics cluster. It includes the complete chain of academic knowledge & research, application development, and original equipment manufacturers (OEMs) combined with a wide range of component suppliers to industries like aerospace, agriculture & food, ICT, maritime, health & life science equipment, automotive, manufacturing industry, energy, infrastructure, building & construction, semicon. The TU Delft Campus provides an inspiring ecosystem for the university, HBO, knowledge institute and many companies focusing mainly on technologies such as imaging, spectroscopy, nanophotonics, opto-mechatronics, optics-design manufacturing, (fiber-) sensors, biomedical optics as well as vision & AI. There are also development activities for the emerging field of quantum optics.

- In the North of the Netherlands there are strong activities in material development for light detection and photovoltaics.

2. Applications and technologies

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

2.1 Status and progress

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

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

Photonic technologies and applications are developing rapidly in the Netherlands. This section reviews some of these developments.

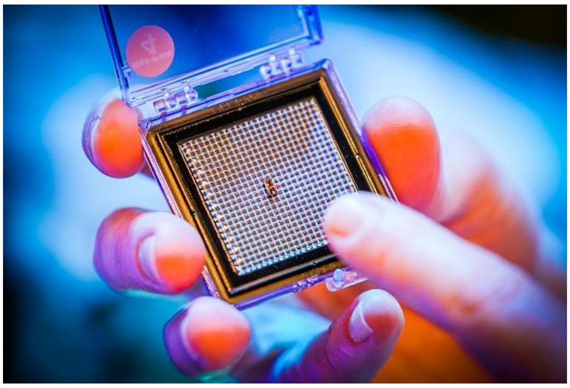
- **New materials, methods, and processes:**
  One of the pillars of new optical technologies is innovations in material science and ways to analyze, engineer, and process a broad range of materials. These materials include glasses, semiconductors, plasmonic materials, metamaterials, gradient index materials,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

Adjustment of equipment for high volume lens replication [photo credit Anteryon]

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

components enables the application of ultra-compact optical systems. 3D printing also enables full 3D-freeform gradient index optical elements in which the optical properties vary throughout the volume of the optical element.
Innovations in materials and their processing enable photonic devices with improved efficiency and flexibility, in extreme environmental conditions, and in combination with other key enabling technologies such as microelectronics. New methods, processes, and equipment for optics manufacturing are being explored and continuously improved. This includes injection molding, diamond turning, magneto-rheological finishing, robot polishing, and 3D printing of large-scale (mm's to cm's) and nanoscale structures.

- **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 lens aberrations), 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.



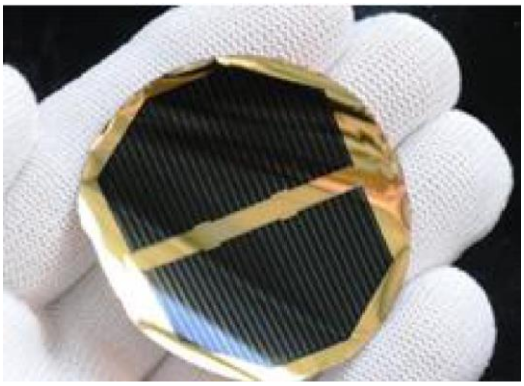
SMART Photonics in Eindhoven is an Indium Phosphide foundry of Photonics integrated circuits [photo credit Dutch Technology Week].

- **Integrated Photonics Manufacturing:**
  This includes the development of generic integration platforms and foundry models. Addressed technologies comprise III-V semiconductors (e.g. InP), TriPleX, and SOI, Monolithic integration of functional materials into the more mature platforms to enhance functionality, CMOS post-processing; assembly, alignment, and fixation, RF processing in the 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 applications of next-generation Photonic ICs (PICs). PICs for example are being used for gas (environmental) sensors, communications, (neuromorphic) computing, LiDAR, biomedical imaging, metrology, and quantum communications.

- **Photonic Integrated Circuits for advanced computing:**
  Photonic integrated circuits (PICs) 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 the University of Twente have relevant research lines on these topics, and the start-up QuiX Quantum is bringing PIC-based quantum computing to the market. Given the PIC technology manufacturing ecosystem present here, and recognizing that AI is mostly driven by efficient hardware, the clear opportunity is to develop a key link in the value chain of AI, thereby creating a strategic position in a huge future growth market. Opportunities that build on Dutch strengths.

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

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



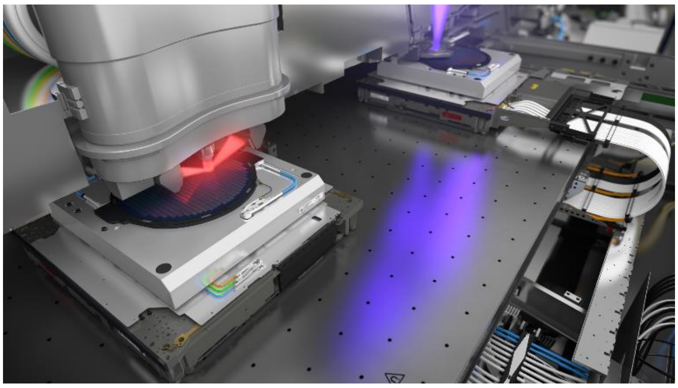
- **Generation of Light:**
  Sources include integrated lasers, solid-state green LEDs, photonic crystal lasers and materials for light conversion (such as phosphors and quantum dots), quantum cascade lasers, VCSELs, supercontinuum sources, plasma sources, ultra-short pulses, high-power lasers, THz sources,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

- **Light propagation, manipulation, and detection:**
  This is a broad, active field of innovation. It includes research on light in optical fibers and beam shaping, deflection, and scattering of light. Light may be spatially modulated by refractive, diffractive, and adaptive optical elements. Light may also be manipulated by interaction with waves, such as with plasmons, phonons, or light waves. This may be used for novel types of spectroscopy and microscopy also at sub-wavelength scale. Detection can be done down to single-photon sensitivity with modern semiconductor devices.

- **Photovoltaics and sunlight-driven chemical processes:**
  Solar panels play an increasingly important role in energy production, driven by innovations that push efficiency up, and module cost down, for Si panels. To break through the efficiency ceiling of Si photovoltaics, current research focuses on nanophotonic light management strategies and

novel materials such as perovskites. At the same time, photonic engineering promises architecture-integrated photovoltaics.
Sunlight-driven chemical processes use sunlight as an energy source for the production of green hydrogen and converting CO_2 into C1 gasses and fuels. When successful this will contribute to the world's climate goals. Optical technology is needed for sensing and additional illumination.

- **Quantum optics:**
  Quantum networks connecting and entangling long-lived qubits via photonic channels may enable new experiments in quantum science as well as a range of applications such as secure information exchange between multiple nodes, distributed quantum computing, clock synchronization, and quantum sensor networks. A key building block for long-distance entanglement distribution via optical fibers is the generation of entangled photonic telecom-wavelength qubits. Such building blocks, and many other quantum-related systems, are now developed and analyzed in the Netherlands cooperating in QuTech with world-leading companies such as Microsoft.
  In May 2020, Minister of Education, 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'.



Schematic view of the metrology and exposure stages for semiconductor wafers in an EUV lithography system [photo credit ASML]

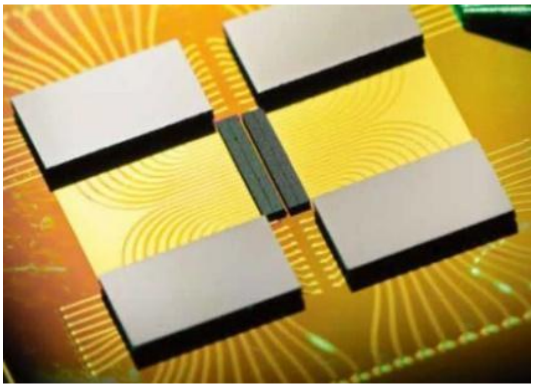
- **Quantum photonic technologies:** Technologies that use the quantum nature of light to achieve computation, communication, or sensing tasks at levels not possible with classical technology. These technologies rely on Integrated Photonics both as an enabling technology and as the core component. Applications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

- **Virtual reality, augmented reality:**
  The technology of virtual reality (VR) 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 broad use in industrial and medical applications. AR combined with special cameras and spectrometers create images that are beyond the limit of the human eye. Smart optical design is required to ensure that all of this can be fitted into wearables.

- **Next-generation optical metrology:**
  Metrology for nanolithography systems and semiconductor wafer metrology will benefit from innovative coherent light sources, optical components such as lenses and (freeform) mirrors with extreme performance, detectors, and optical lightpaths, at wavelengths from the infrared down to soft-X-ray. Researchers in the Netherlands develop such methods, systems, sub-systems, components, and signal-processing algorithms. To meet the semiconductor metrology challenges of tomorrow, it is necessary to be successful in many optics-related disciplines which have to be integrated into practical, robust, and versatile systems.

- **3D-metrology for robots:**
  The digitization of the manufacturing industry is one of the central themes for the Netherlands. This transformation is necessary to increase productivity, address the growing scarcity of qualified personnel, and promote future economic growth, making the 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 the dimensions, position, and orientation of objects during manufacturing and automated assembly processes, as the "eyes" of the robots. The rapid development of LiDAR is also finding new applications in robotics, drones, and agriculture. Some of the building blocks of this type of systems are available; however, the integrated intelligent "robot & sensor" systems are still to be developed. We foresee that the future availability of affordable intelligent robots, equipped with several different types of sensors, will be a huge boost for the application of robots in the manufacturing industry.

- **Sensors for AgriFood:**
  The need for more food grown in a sustainable way, depletion of resources, pollution, reducing waste, and the ever-rising cost of fertilizers and pesticides are all drivers towards a new way of sustainable precision farming and a more efficient supply chain. Information and hence sensors play a pivotal role in this. Photonic sensors are very well suited for remote sensing in qualitative and quantitative ways. Hyperspectral imaging, (IR) spectroscopy, photoacoustic gas sensing, speckle imaging, and biosensors are examples.
  It is possible to measure ammonia and methane in the air, sugar content in fruit, or the composition of milk directly after milking this way. Also, biosensors could replace time-consuming lab analysis in food processing. There is a special program on precision agriculture in the National Growth Fund (PhotonDelta) with a range of new sensing solutions being planned to determine growth conditions, soil health, post-harvest produce conditions, and composition. Among others, One Planet in Wageningen has a strong R&D facility. Several start-ups, like MantiSpectra (NIR sensors), and Spectrik (ammonia and other gas detection) have developed promising applications.



Massive Parallel Interconnect
[photo credit University of Eindhoven]

- **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.
  Several 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 Netherlands. Companies like SpaceX and Facebook also have ambitious plans for such space-based networks.
  Dutch companies, such as VDL, DEMCOM Focal, TNO, LioniX International, and Nedinsco, are active in this field. Several Dutch companies are involved in space technology, like Airbus Defence

and Space, Hyperion Technologies, and ISIS, which are good at building satellites. FSO-Instruments has been founded to commercialize Laser Satcom optical-communication components, sub-systems, and terminals. Research on different aspects of optical communication, for both terrestrial and space applications, is performed by 3 technical universities (Delft, Eindhoven, Twente) and at KNMI, VU Amsterdam, and Leiden University.

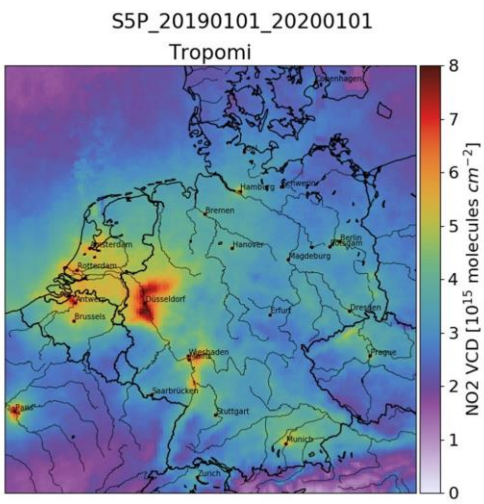
- **Data and telecom transceivers and photonic systems:**
  The exponential growth in broadband demand and speed is continuously pushing the development of communication infrastructure across all domains (from fiber to the home (FTTH) to long-haul networks). The underlying deployment of enhanced optical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

2.2 Developments in present and future markets and societal themes

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

1. Climate – including energy and water

The monitoring of water is expected to become a big issue in the next decade as the water supply in the Netherlands is under strain due to climate change and pollution. Regional shortages of fresh water are already occurring during peak periods. Quick actions are needed to prevent drinking water shortages by 2030. Optical monitoring with fiber Bragg grating in aquifers, spectroscopic monitors on land, and satellite observation from space can help to direct and evaluate actions to improve water quality subscript.



TROPOMI NO2 measurements [photo credit TNO]

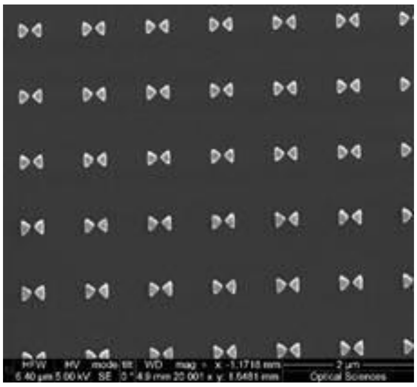
The transition to a sustainable, smart energy system builds on renewable energy sources such as solar-, wind- and bio-energy. Light is one of the important energy sources. Photonics, therefore, plays a crucial role in the energy transition. Novel photovoltaic materials, new manufacturing techniques, and improved light management in solar cells boost the efficiency of solar cells towards the Shockley-Queisser limit. The development of flexible form factors 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, the photonic monitoring of mechanical stability in windmill propeller blades.

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

Societies around the world already face 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 the rising sea level. These adaptations need to take place at the right moment and smartly and efficiently. As such, we can help prevent or reduce the risk of natural disasters, social and economic damage, and political tensions.

The Paris Climate Agreement aims to reduce the harmful impact of greenhouse gasses on our environment. One of the challenges of reducing emissions under this agreement is the limited number of available, accurate emissions measurements. Optical technologies are vital in performing these measurements. Some examples include (compact) instrument design for earth observation using freeform optics design and other photonic technologies (i.e. TROPOMI and SENTINEL V). Besides satellite-based sensing, cloud-connected, smart photonic sensing systems for pervasive community-based environmental pollution monitoring are needed as well. They can contribute to real-time citizen alerts on local pollution levels and related health risks. Next to environmental gas measurements monitoring water quality is essential as well. Waveguide-based Surface-enhanced Raman spectroscopy (i.e., waveguide SERS) is one of the examples of photonics-based detection equipment for measuring pollutants in drinking water. Next to environmental gas measurements monitoring water quality is essential as well. Waveguide-based Surface-enhanced Raman spectroscopy (i.e., waveguide SERS) is one example of photonics-based detection equipment for measuring pollutants in drinking water.



Optical nanoantenna's for SERS [photo credit Mesa+]

Further examples of needed Photonics technologies to fight climate change are structural integrity monitoring in large constructions such as dikes, bridges, and flood control dams. Photonics 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 and installed a NWA route "meten & detecteren". In this route, metrology for both climate and health technologies will be developed.

In the energy transition "sunlight to chemicals" will play an important role. Using photo-chemistry a process an energy storage buffer can be created while simultaneously reducing CO2 emissions. Examples of possible storage buffers are green hydrogen, green syngas, and methanol. Necessary optical technologies are optical sensors, optical system design of illumination optics, solar cell optimization, and integration into novel flow reactors.

2. Sustainability & Circularity

The AgriFood 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 Wageningen University and other research organizations.

Photonic sensors (using Infrared Spectroscopy) also monitor the quality of food for food safety purposes, for example, 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, which have identified challenges in yield monitoring that could be solved with light-based sensors.

Photonics for precision farming.
[photo credit Avantes BV]

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

Photonics contributes to the circular economy using 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.

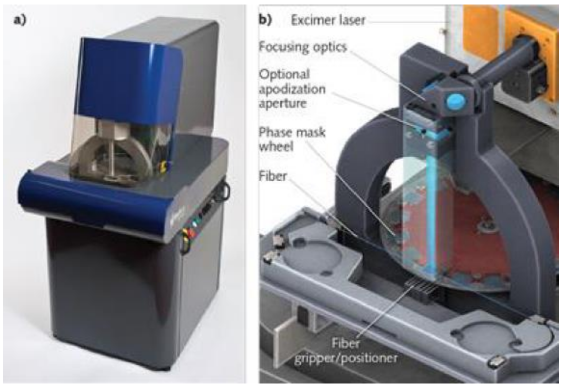
Furthermore, it leads to precision instruments assisting the development and production of products 'first time right', as well as to the development of inherently reusable products. Furthermore, Photonics provide novel and more insights into growth conditions in agriculture, helping the reduction of nutrients needed and therefore lowering the footprint. As one-third of the food grown in the world is lost along the supply chain, novel technologies to detect pests, molds, diseases or damage can help a lot, and optical technologies are well suited to do so. By integration, they can become small and robust and suitable to fit on robots or drones.

Digitization of the industry ("Smart Industry") is crucial for sustaining international competitiveness, employment, product innovation, and greener industry. It will enable a fully digitized and connected value chain from supplier to customer with an emphasis on high-precision, cost-competitive, and resource-efficient production, fast and flexible mass customization, and new (data-driven) services. This transformation is driven by new manufacturing and communication technologies.

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

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

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 PICs) make mass-manufacturable photonic solutions possible.



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

A few additional photonic technologies for growing industrial applications are listed below:

- High-power lasers for industrial processing.
- The industrial production of micro and nanomaterials and structures using high-performance lasers.
- Fiber optics as the backbone of the Industrial Internet.
- Use of optics for additive manufacturing (3D printing) and mass customization.
- Optical computing underlying artificial intelligence and smart robotics.
- Rich visual communications such as ultrahigh-resolution cameras, augmented reality, and 3D display technology.
- Optical sensors are increasingly important for sorting and measuring the purity of materials leading to better re-use.

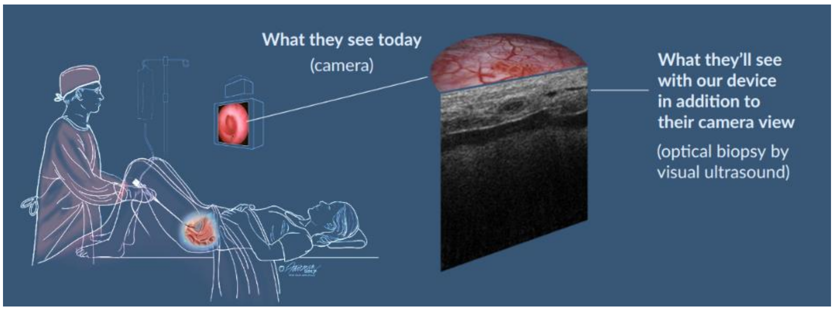
3. Health Monitoring and Diagnostics

Healthcare is facing growing demands in developed, as well as developing countries due to increased longevity resulting in more people with chronic diseases at later stages of their lives. Better healthcare leads to an increase in quality of life.

This increase in demand for healthcare is exerting constant pressure on healthcare systems. Therefore, prevention rather than treatment of diseases is of growing importance. Medical diagnostics moves from current, cost-intensive, centralized diagnostics after the onset of a disease, to the detection and prevention at the earliest possible stage by new (handheld) diagnostic instruments. Handheld diagnostics and treatments make point-of-care diagnostics, as well as better critical care, possible. Miniaturization of medical devices can bring healthcare from the clinic to 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 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 lifelong exposure health could be predicted.

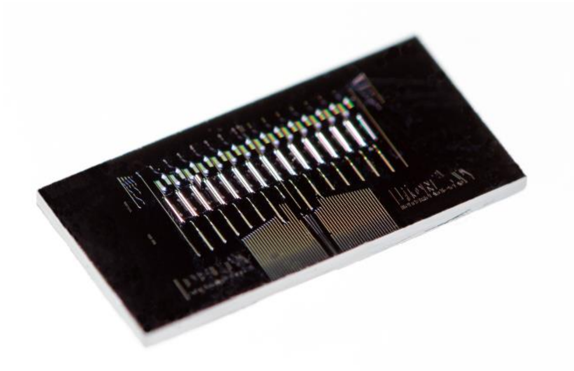
Medical Photonics is one of the major application domains of Photonics. There are many ways in which Photonics supports the medical field.



OCT catheters used for bladder cancer diagnosis [photo credit Scinvivo]

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), microelectronics, 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 International, Delta Diagnostics) coherent detection, optical coherence tomography systems, SPECT, Raman (CARS) based diagnostic systems, photoacoustic imaging technologies, advanced retinal imaging for early disease screening and detection, photonic health patches. Miniaturization of these photonic components in medical devices is an important challenge for future R&D in Photonics.

Advanced (medical) Photonics also offers non-invasive monitoring, for example through the skin with light-spectroscopy, and minimally 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 e-health makes use of imaging sensors.


Label-free biosensor PIC of Delta Diagnostics for biomolecular interaction analysis and protein quantitation [photo credit DeltaDiagnostics]

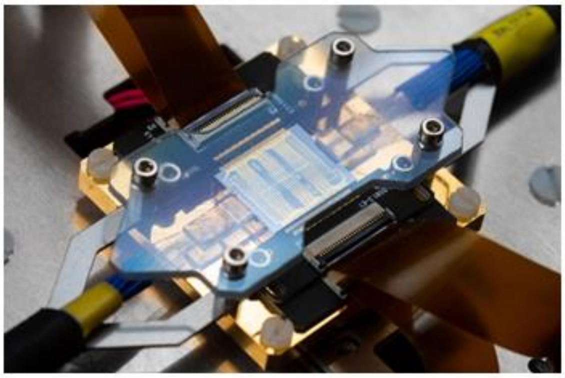
Bio-sensing using Integrated Photonics is one of the promising application areas, which makes instant and accurate (viral disease) diagnosis possible. Companies and institutes are developing Photonics enabled bio sensing tests that can be used for fast real-time (and on-site) detection of pathogens which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

The use of virtual reality (VR) and augmented reality (AR) promises many benefits for older adults, such as promoting a healthy lifestyle with health-related gaming, maintaining social contact via digital interfaces, supporting rehabilitation, and aiding in everyday life tasks. The use of VR and AR in psychotherapy and rehabilitation can contribute to maintaining older adults' motor abilities, fitness, balance, and memory. Moreover, VR intervention programs can be used to train cognitive and physical functions in older adults with mild cognitive impairments.

4. Safety and 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) financial status (e.g. online payment transactions, online insurance), and consumption patterns (e.g. retail information). Also, our devices, machines, and vehicles are increasingly connected under the frame of smart homes, smart factories, and smart cars. Protection of privacy, individual identity, and secure data networks must be guaranteed.

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



A close-up of a 12/12 quantum processor [photo credit QuiX Quantum]

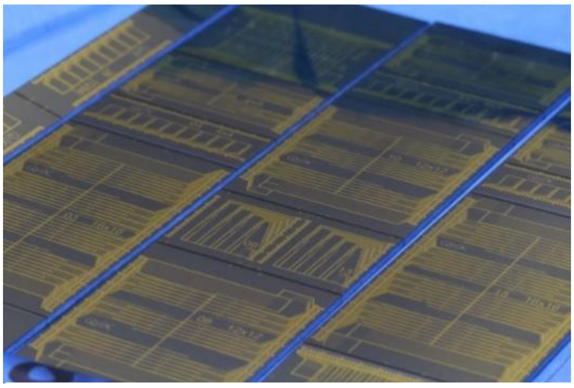
Quantum technologies are a key component of a future safe society. Photonics plays a key role in all three branches of quantum technologies, which are: computation, communication, and sensing. All three sectors are predicted to undergo substantial growth above GDP growth in the coming years.

For *computation*, large-scale tunable integrated photonic chips play a 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.

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, free-space optics for short-distance links and quantum satellite connections, and Integrated Photonics 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 a non-spoofable 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.

The physical infrastructure also needs to be protected from threats. Dikes, roads, and bridges need to be protected from environmental impact and can be monitored by Photonics sensors. Security in the 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.

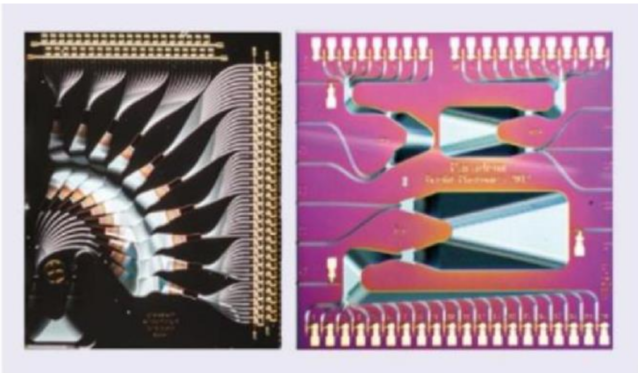


A series of QuiX quantum photonic processors [photo credit QuiX Quantum]

With financial support from MESA+, we started a project to detect COVID-19 biomarkers with 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, pollution, and 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.



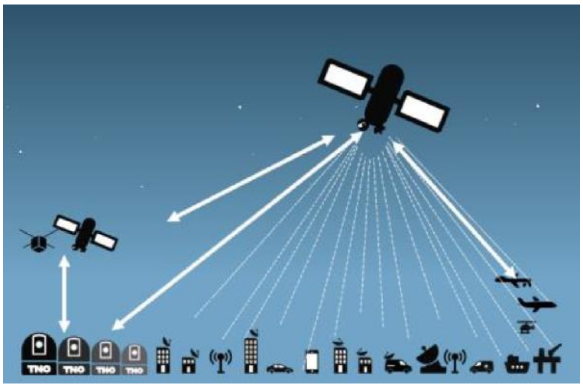
Readout system for Fiber Optic Sensors [photo credit JePPIX]

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

Beyond fifth-generation (5G) mobile, wireless optical communication will be able to solve some of the challenges ahead for the automotive industry. In autonomous driving communication with 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 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.



Laser Satellite Communication [photo credit 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 provide 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).

Optical metrology has been the main metrology modality and will be extended into shorter wavelengths ((soft) x-ray domains) on one hand and towards longer wavelengths with larger penetration depth on the other side.

2.3 Conditions and milestones for this roadmap in 2030

The Netherlands has traditionally played a leading role in photonics innovation and presently houses the world-leading high-tech semiconductor and life science industry, to which Photonics and Optics are a central theme. Semiconductor metrology as performed by companies such as ASML requires the most advanced optical technology available. Fundamental research, in close collaboration with industry to enable a rapid path to applications, is a strength of Dutch academia that enables companies to thrive.

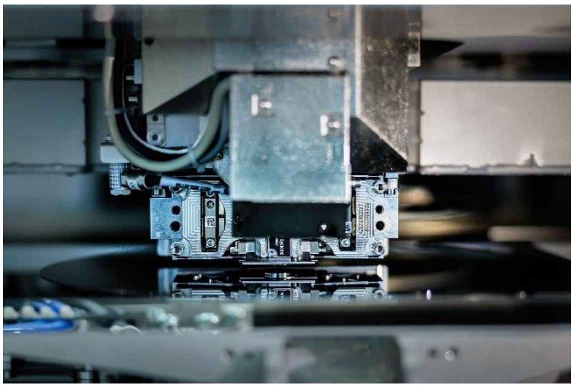
In the recent European Commission and European Investment Bank report on "*Financing the Digital Transformation: Unlocking the Value of Photonics and Microelectronics*" (2022), Photonics technologies are regarded as "one of the essential key enabling building blocks for the digital transformation of Europe".

The European coordination of Photonics is exemplary: the Horizon Europe 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 that has been recognized as the best PPP in Horizon Europe by the Commission's independent evaluators and demonstrated by the PPP's impact on jobs and growth in Europe.

Augmented Reality
[photo credit TNO]

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

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

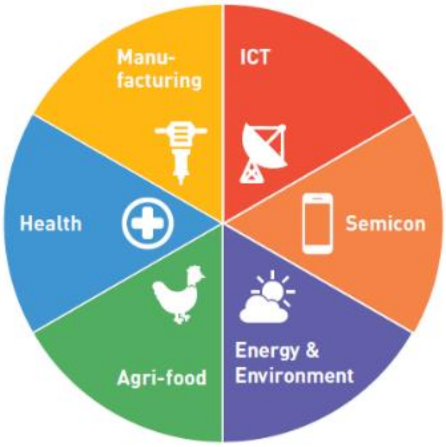


YieldStar scatterometry for accurate and fast semiconductor wafer metrology
[photo credit ASML]

2.4 Dutch vision and synergy with National Agenda Photonics

This Photonics roadmap is based on our vision of 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 (NAF) 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", decreasing the energy need of data centers by Integrated Photonics, and increasing bandwidth through Laser Satellite communication.

- 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). Next, there is also an industry that manufactures optical components.

- Photonics for Energy and environment: more energy-efficient photovoltaics, climate monitoring by remote sensing, efficient lighting, and new solar fuel programs.

- Photonics for AgriFood: sensor systems for precision farming, and efficient lighting for optimizing the production of food; sensors for (food) quality monitoring. Sensors for nitrogen compound monitoring.

Further elaboration of these topics is needed, including prioritization and synchronization with priorities at a European level. This synchronization will also help to increase the Dutch role in European Photonics projects. PhotonicsNL collaborates on some projects, such as BestPhorm21 and Phorwards21, that will start in January 2024.

3. Priorities and implementation

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

- Photonics research and development must center around realizing novel techniques and devices that can contribute to societal challenges. A well-coordinated effort with innovation potential, starting in academia, can lead to start-ups, and that possibility should be emphasized and stimulated.

- In our national ecosystem we need companies, virtual or physical labs, and R&D programs aimed at integrating and testing PICs into modules and systems for practical applications. Basically a link between Optics Netherlands 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 the workforce and providing access to state-of-the-art manufacturing technologies

- Creating regional Digital Innovation Hubs, a.k.a. field labs, or other ecosystems to develop innovative new photonic solutions. This extends beyond the photonic technologies to include the adjacent technologies: high-speed electronics, mechatronics systems, and systems for large-scale data processing. What we need to build in our national ecosystem: companies, virtual or physical labs, and R&D programs aimed at integrating and testing PICs into modules and systems for practical applications. Basically a link between the Optics Netherlands and PhotonDelta ecosystems.

- Innovations are required in assembly technologies to enable competitive advantage from within the Netherlands. A paradigm shift in the cost model for hardware assembly can lead to the reshoring of manufacturing. This includes the complete process chain of "Additive Manufacturing" from CAD model to the product, and the development of wafer-scale processing for both optics and smart systems incorporating combinations of optics, Photonics, and electronics.

- Within the Quantum Delta Growth Fund (QDGF) project, significant effort is aligned with photonic technologies. All three KAT programs are making use of photonic technologies. In KAT-1 Photonics is used for creating cold-atom based quantum computers with arrays of optical tweezers. In the KAT-2 program, quantum secure optical networks and the required components for building them are investigated for both quantum key distribution and quantum internet. Finally, within KAT-3, optically trapped cold atoms are used for some of the quantum sensing applications. In addition through the QDGF project, significant investment in NanoLab@NL is being realized enabling next-generation research and innovation in photonic technologies with a total investment of ~100 M€.

- Several initiatives (on both national and regional levels) have been set up by the clusters, Photon Delta, PhotonicsNL, and Optics Netherlands. Photonics is now acknowledged to have priority status on a national level (Ministry of Economic Affairs and Climate) and regional level (provinces and development agencies) leading to joint efforts by the clusters to thrive for an increased level of innovation in Photonics with involvement of a broad network between academia, knowledge institutes and industry. It is essential that these actions continue.

- PhotonicsNL, Optics Netherlands, PhotonDelta, and NWO will give support with setting up and maintaining the Photonics Roadmap.

- Valorization projects will be carried out together with TNO/GTIs including projects with SMEs and links with IPCs and other Innovation Funds to secure commercialization and market introduction for innovative components and systems. The PhotonDelta Growth Fund is set up to invest 1.1 B€ in the coming 6 years in Integrated Photonics through technology development applications, industrialization, and supporting start-ups.

- Photonics is a driving force in the fundamental research programs of NWO, and the EU program Horizon Europe, in which the European Partnership for Photonics is a candidate in the area of digital, industry, and space.

- Photonics (light-based technologies) is described as an essential building block for digital transformation and a green and healthy future in Europe. This partnership aims to speed up photonic innovations, secure Europe's technological sovereignty, raise the competitiveness of Europe's economy, and ensure 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.

Innovative full-colored bulb based on a light guide for high-quality color and white [photo credit Signify].

- The Knowledge and Innovation Agenda 2018-2021 and the process from this towards a new agenda, a new 'National Technology Strategy' for the coming years underlines the importance of Photonics as a key technology. If we furthermore want to make an active and targeted connection with our societal challenges 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, we need to build a more connected infrastructure, based on innovation collaboration in recognizable Photonic Technology Centers (PTCs) with jointly established R&D agendas and top facilities. The Chip Integration Technology Center (CITC) and Photonic Integration Technology Center (PITC) are the first, important examples of this, which will enable tight cooperation between knowledge institutes and industry, and will play a key role in establishing 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 120 SMEs embracing Photonics for innovation (see overview in Chapter 4).

As such, a flourishing Photonics ecosystem is active in the Netherlands addressing the complete value chain; three cluster organizations jointly coordinate the ecosystems: PhotonicsNL, Optics Netherlands, and PhotonDelta. Together these organizations regularly initiate activities including joint promotion and business development of the Dutch Photonics industry (in international exhibitions and trade missions), the definition of joint research plans in Photonics, and joint synchronization meetings with the government and connecting with other Dutch focus areas like Quantum and the Agrofood sector to support these sectors with new 'key technologies'.

Photonics NL: the National Association for Photonics and Optics in the Netherlands. The main goal of PhotonicsNL is to stimulate photonics and optics innovation and economic activity. Their vision is that they enable collaborations and cross-fertilization in the photonics value chain, propagate the importance of photonics for our economy and at all levels of education, and promote the national photonics community in the Netherlands and abroad. To achieve this they organize networking, knowledge, and matchmaking events, participate in international trade missions, create links between their members, and collaborate in European Projects and with other national clusters.

Optics Netherlands is a consortium of knowledge institutes with the involvement of more than 150 High Tech companies from all over the Netherlands. It is a 4TU institute to boost Dutch industry in the field of optics and opto-mechatronics and increase 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 Optics Netherlands the academic partners and 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 opto-mechanical 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 (PPP) and has a proven track record with initiation and execution of more than 35 M€ in research projects and over 20 M€ in development projects.

PhotonDelta is a growth accelerator and ecosystem developer for the Dutch integrated photonic sector as well as an investor in startups and SMEs. In 2022 the PhotonDelta Growth Fund was awarded by the Dutch government. This 1.1 B€ program over the next 6 years is set up to realize economic development in Integrated Photonics in the Netherlands to add 6 B€ in value by 2030. To realize this goal, development programs in technology and applications will be executed as well as industrialization programs. Also, training and developing the number of people working in the sector is part of it. Application domains are datacom/telecom, healthcare, mobility, and AgriFood. Funds are reserved to support startups and SMEs. PhotonDelta was initiated in 2016 as an open-innovation project launched by Eindhoven University of Technology, after which it soon expanded its scope to a national level with Eindhoven, Twente, Nijmegen, and Delft regions, involving companies and public investors 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 globally recognized innovation hub that has invested with partners more than 200 M€ in start-ups. 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. Several 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.

Amsterdam Science Park - ARCNL and AMOLF: The NWO institute ARCNL is a public-private partnership between VU, UvA, NWO, and ASML. They perform fundamental research with a strong application perspective towards breakthrough technologies for extreme ultraviolet (EUV) lithography. Photonics is a major theme in their work, and they have strong expertise in EUV light sources, optical metrology, laser systems, computational imaging, spectroscopy, and optics in general. They collaborate with the adjacent **AMOLF** institute with 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.

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 which 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 Focus Group on organic photovoltaics and the TU/e-DIFFER effort on solar fuels.

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

IMEC has become more important in 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 the development of the next generation, of thin film solar cells. Solliance was founded in 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 development 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 various sensing applications such as 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 (PICs)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 PhotonDelta 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 (PICs) 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.

The **IEEE Photonic Society Benelux** is a sub-chapter of the International Photonic Society of the IEEE and was 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 that 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 Link with other innovation instruments (e.g., public purchasing and risk investment)

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

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

- Free Form Scattering Optics. This program enables high-tech optical devices that contribute to energy efficiency, climate change, internet-of-things, food and water quality and quantity, and security, in the interest of rendering unstoppable worldwide sustainable urbanization.

- LINX (Lensless imaging of 3D nanostructures using soft-X-rays) program started in 2018 and is a collaboration between 5 academic partners and 7 industrial users (budget 4.2 M€). The central theme of this program 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 instrument 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) program focuses on the fundamental physics involved in current and future key technologies in nanolithography, primarily for the semiconductor industry (budget 9 M€ with equal contributions of 4.5 M€ from NWO and ASML, respectively).

- OPTIC (Optical coherence; optimal delivery and positioning) is a collaboration of five academic partners and six industry partners to improve the optical functionalities and efficiencies of innovative high-tech devices. Three major relevant Dutch high-tech industries - semiconductor nanofabrication, lighting, and satellites - share common optical technology challenges for their devices. Mathematics, optics, and physics researchers in academia work on novel optical coherence technology in collaboration with industrial partners to address these challenges. OPTIC takes a step forward by the combination of freeform optics on the macroscale and wavefront shaping on the microscale.

- MEDPHOT (Photonics Translational Research - Medical Photonics) program wants to develop a light-based counterpart of a PET scan and is a collaboration between three UMCs, 12 industrial partners, four universities, and TNO (total budget 5.3 M€).

- 3D Nanoscale Imaging (3DNI) is a program aiming to develop technology for making 3D images, super-fast, and on an extremely small nanometer scale. This program is a collaboration of three universities, three UMCs, and seven companies (budget: 3.3 M€).

- Optical Wireless Superhighways: Free photons (at home and in space) (FREE) is a program in which research into optical free-space communication to replace radio frequencies is done. The program is a collaboration between five universities, 14 companies, and two knowledge institutes (budget 5.6 M€).

- Steering and sensing sustainable CATalytic reactions with Light (CATLight). This project is a collaboration between AMOLF and University Utrecht in collaboration with six companies (budget ~ 2 M€).

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

Valorization

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

There are generic valorization instruments in use, managed by the Dutch Enterprise Agency (RVO), NOW, Regional Development Agencies, and the European Union (SME Instrument). The technologies should use these as much as possible.

- Programs from the Dutch Enterprise Agency (RVO) that give specific attention to small companies, Seed Capital program, Vroege Fase Financiering, Innovatie Krediet.
- PhotonDelta has leveraged the interest of 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), demonstrator (technology development) programs (4 M€/y), and possibilities for industrial partnership programs (IPP). A good financing climate is of great importance.

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

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

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

Expected impacts addressed: #19 (Green), #20 (Data), #21 (Industrial leadership and autonomy), #22 (Digital and emerging enabling technology sovereignty), #23 (Space)

Objective: establish European technology and data sovereignty and supply chains by developing cutting edge Photonics technology platforms and manufacturing key Photonics components and systems to enable the digital and green transformation of the European economy and society.

Achievements sought / targets:

- Foster world leadership in Photonics: by incorporating new technology concepts and platforms such as digital Photonics, computational 3D imaging, mixed reality, Integrated Photonics, micro- and nanophotonics, plasmonics, metamaterials, quantum optics.

- Digitize European Industry: provide critical Photonics core technologies to strategic European industry sectors

As a 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 and ChipsAct, Made Europe, AI, data and robotics, Smart Networks and Services, Global competitive space systems, HPC, Smart Farming, Towards zero-emission road transport, and 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), Petra Wicherink (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), Hans van den Vlekkert (LioniX, QuiX), Pepijn Pinkse (UT, MESA+, ANP), Eric de Leeuw (Diamond Kimberlit), Benno Oderkerk (Avantes), 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 (Egg Select BV), 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, Michel Verhaegen (TUD), Remco Nieuwland (SOMNI), Marco Snikkers (Ocean Insight).

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

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 was coordinated by PhotonicsNL - Ron van der Kolk and Petra Wicherink, Optics Netherlands/TUDelft - Anke Peters, NWO ENW - Silke Diedenhofen, NWO TTW - Paul Schuddeboom, Eddy Schipper (RVO) and Hans van den Vlekkert (LioniX International), in collaboration with many others. A set of recent Dutch, European, and global documents on Photonics has been used as a reference (see footnotes).

In 2023, the roadmap has been updated according to recent developments in the Photonics ecosystem, with the grateful help of the writing team:

Benno Oderkerk (PhotonicsNL), Anke Peters (TU Delft/Optics Netherlands), Petra Wicherink (PhotonicsNL), Stefan Bäumer (TNO), Jos van Haaren (ASML), Eddy Schipper (RVO), Oded Raz (PhotonDelta), Carol de Vries (PhotonDelta), Silke Diedenhofen (NWO).