2015

Photonics Roadmap

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May 14, 2015

HTSM Photonics Roadmap

2015 - 2019

Contents

1 Societal and Economic Relevance

1.1 Societal challenges addressed in this roadmap

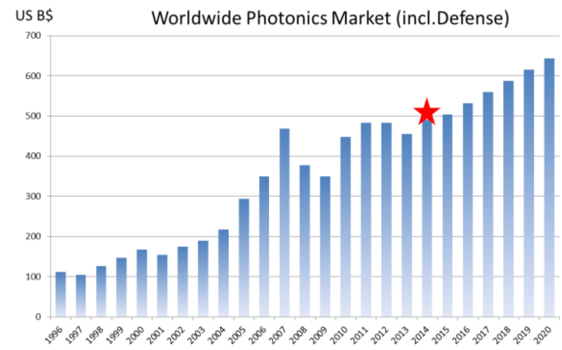
The Photonics contribution to modern society is impressive but not always very visible.
The unique properties of light (colors, speed) together with the recently developed new technologies allows the user of photonic components to bring innovative products in endmarkets that go beyond the national borders. Photonics is science and technology and includes the study of the generation, propagation, modulation, signal processing, switching, amplification, detection and sensing of light.

Photonics is denoted a **Key Enabling Technology (KET)** by the EU and also adopted by the Dutch topsector High Tech Systems and Materials (HTSM). Being a basic technology it provides photonic components that allow innovative solutions in a wide field of applications and contributes directly in search for solutions for the grand societal challenges of our time:

- In **healthcare** (theme 1) by radical new approaches moving from current, cost-intensive treatment after onset of a disease, to the detection and prevention at the earliest possible stage by new (handheld photonics based) diagnostic instruments, which allows to bring these new tools critical care as well as perform remote diagnostics.
- In **energy** saving (theme 3) (“green photonics”) by the introduction of very efficient light sources, (O)LEDs, and energy generation by highly efficient solar cells.
- In **security/safety** (theme 7) by the emerging photonic sensing and imaging technologies for higher levels of security and safety through the use of sophisticated surveillance and encryption technologies both in the field as well as in logistics (e.g. nanodust detection and THz imaging technology).
- In monitoring **climate change** (theme 4) by the earth’s atmosphere observation using advanced optical pollution (gas-) detection.
- In **mobility** (theme 5) by the development of the future multi-terabit internet fed by full Fiber to the Home (FttH) deployment at ever increasing capacity and lower energy in internet datacenters allowing new economic initiatives and reducing traffic congestions (less CO_2) by providing the future proof infrastructure for more homeworking.
- And last but not least Photonics will lead to new innovative entrepreneurships resulting in new captivating jobs for young people and new challenges for education at all levels, from primarily to high level education.

To strengthen the overall competitive position of the Netherlands, photonics will play a pivoting role in the HTSM topsector aiming for the manufacturing of broadly applicable products and services for primarily industrial applications.
The Netherlands has an excellent position to bring photonics into numerous markets. We have a high scientific level in important photonic segments (Dutch universities and NWO initiatives) and a highly qualified high-tech industry with specific nano-electronics and mechatronics expertise. Dutch internationals like ASML, Philips and OCE/Canon are big players in the photonics area but the Netherlands has also more than over 120 SME’s which are already embracing photonics for innovation. A smart photonics ecosystem is active in the Netherlands addressing the full value chain.

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



Source: SPIE

The total world market for photonics in 2015 is estimated as B€ 460 including the defense market, i.e. about 1/5th the size of the electronics market, which is significant when compared to other technology sectors and growing fast. From 2005-2014, the global market showed a real annual growth rate of 5-10% (depending on sector), higher than in many other sectors (Food: 2%, Automotive: 3-5%). The photonics supply and demand is global with 30% within the euro zone. The expected world market for 2020 is B€ 615[1]. Following the Optech study, the Dutch contribution is B€4.4 dominated by production equipment (ASML), lighting (Philips) and printing (OCE/Canon). Medical systems and optical components/systems is estimated to be B€ 0.5. The Netherlands is market leading in the following sectors: production technology in particular lithography, Solid State Lighting, OLED, Medical Technology with Imaging and diagnostics; Integrated Photonics; Optical Measurement, Machine Vision, CCD/CMOS-detectors; ICT: Printing and FttH equipment; Solar; optical Systems and components. Dutch SMEs target profitable niche segments in all photonic market sectors.

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

The Netherlands has an excellent position to bring photonics into numerous markets. We have a strong scientific position in important photonic segments (Dutch universities and NWO initiatives) and a highly qualified high-tech industry with specific nano-electronics and mechatronics expertise. Dutch internationals like ASML, Philips and TE Connectivity are big players in the photonics area but the Netherlands has also over 120 SME's which are already embracing photonics for innovation. A smart photonics ecosystem has been realized in the Netherlands covering the whole value chain. The Photon Delta initiative in Eindhoven brings industry and universities together to foster the Photonic IC technology into different markets. Also in Twente and Delft, industrial activities mark the onset of new market applications based on photonic integrated technology.

The photonics industry has unique positions in medical diagnostics/therapy, data processing, telecommunication (FttH, interconnect), modern lighting systems, consumer sensor/safety, automotive and water. Our strength is in application knowledge and design in high tech systems such as lithography, solid state lighting, generic waferfab processes and platform technologies. The presence of the right industries supports the value chain into commercial successes. International interest to our approach of photonic integration is emerging.

More than 400 M€ (since 1995) has been invested in photonics related infrastructure by industry and government. Knowledge that has been generated by academic groups and R&D institutes is ready for

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[1] Optech Consulting, Studie "Photonik 2013", in: Spectaris, VDMA, ZVEI, BBF, "Branchenreport Photonik 2013".

commercialization. The results of the current SmartMix-Memphis project, IOP-Photonic Devices projects, the Perspective programs of STW, the NWO research programs and the Industrial Partnership Programs of FOM and STW sustain and strengthen this position. In addition, the excellent position of Dutch universities is exemplified by covering almost 35% of the 60M€ European photonic projects on photonic integration technologies. A Dutch photonic network has been established that meets once a year at the Photonics Event (700 participants-2014) and the PhotonicsNL association supports the photonics network both on a national as EU level.

2 Application and technologies

2.1 State of the art for industry and science

The strong academic tradition in the Netherlands in optics is the basis for the flourishing applied research in the Dutch high tech industry. Optics has since many years been one of the core disciplines of leading industries such as Philips and ASML. Besides these multinationals, there are many very innovative Dutch SME's active in the field.

During the last decades there is a trend towards miniaturization and integration. The development of optical communication, optical data processing and the growth of the electronics- and ICT industries has led to "integrated optics" and "photonic integration". In this discipline the methodology in semicon manufacturing is applied to realize many optical functions on a single chip. Successful technologies use InP and TriPleX materials.

Photonics spans the entire field from coatings, free forms in imaging and non-imaging systems, fiber optics for communication, integrated optics, (near-field) microscopy, (bio)- medical optics, laser technology, nonlinear optics, (remote) sensing, metrology, spectroscopy, nano photonics, plasmonics, metamaterials, to quantum optics and quantum communication. Current Dutch academic research is at the fore-front of many of these topics and the Dutch photonics industry is applying their results more and more.

The opportunities of photonics in general and the benefits of generic foundry-based technologies are addressed in three major national R&D-programs: IOP Photonic Devices, STW Perspectief "Memphis" and STW's "Generic Technology for Integrated Photonics" and "Smart Optical Systems" which initiated successful collaborative consortia between industry and universities and have put the Netherlands at the forefront of Photonics technology development. The JePPIX organization assists users around the globe to get access to advanced fabrication facilities for Photonic Integrated Circuits. JePPIX has recently published its 2015 roadmap[2].

Following the recommendations of the previous roadmap, two PPP STW Perspectief Programs have been initiated, granted and started:

MemphisII with 7 university research groups and 20 industrial partners (budget 6 M€ and industry contribution of 2.6 M€ in cash+in kind).

Cancer ID with 7 academic research groups and 22 industrial partners (budget 4,7 M€ and industry contribution of 1.7 M€ in cash+in kind).

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[2] http://www.jeppix.eu/document_store/JePPIXRoadmap2015.pdf

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

2.2 Research, development and innovation priorities in present and future markets

The Dutch High-Tech industry is increasingly embracing photonics in its innovation. Photonic technology is maturing rapidly. Unique for the Netherlands is that all photonics expertise is available and when matched to our High Tech strength, the industry has the potential to become a major player in this field. The enabling character of the photonics industry matches very well with the Top Sectors and is one of the technology “backbones” of the HTSM sector. Although not all devices and functions can be realized on a chip with sufficient performance, we nevertheless expect in the coming years a rapid growth in the development and the application of photonic integration technologies, similar to electronics, where micro and nano-electronic integration technologies have enabled electronics to change our world. Major sectors of activity in the Netherlands where photonics is used are:

Production technology for semiconductor industry e.g. optical lithography

Lighting: In the next 3 to 4 decades the demand for artificial light is expected to triple by much more efficient solid state light sources, such as LEDs and OLEDs.

Information and communication technology: digital photo copiers and printers based on laser and LED technology. Fiber-to-the-Home networks and high speed interconnections and energy efficient datacenters.

Medical technology and life science: advanced microscopy and other emerging tools used in medical and life science research and applications in the clinic.

Optical components and systems – e.g. fiber based and adaptive optics - will contribute to the development of new photonic based systems.

Apart from these areas, we envisage that the Netherlands will be strong in the following fields as well: image technologies, communication, data processing, manufacturing and packaging technologies, security, novel or emerging materials, sensors and bio-sensors.

Vision and Ambition

Photonics is one of the most important key technologies for the 21st century enabling solutions for the societal challenges the world is facing. History shows that scientific and technological breakthroughs lead to new and revolutionary industrial activities and continue in the decades after the invention. The 21st century is the century of the photon and with the knowledge and technological breakthroughs we are ready to profit from the photonic revolution: achieving a new level in the generation, control and the application of light in many high tech markets where Dutch industry and knowledge institutes will play a prominent role.

Our ambitions are:

- Exploit our generic integrated photonics technology into business
- Continue R&D with focus on the photonics value chain for next gen products
- Strengthen the micro-optics, display technology and packaging technologies
- Participate in Photonics21 and in H2020/ECSEL projects
- Doubling exports in the period 2015 – 2025
- Job creation by facilitating education in the field of high tech and photonics

2.3 Application and technology questions to be resolved for this roadmap until 2025

In this section a summary of research topics is provided of the broad field supported by photonics. To provide a guideline, these activities are grouped in four themes: i) Applications generating the requirements for the components from the market,
ii) Components and Systems describe the component performance needed for the applications,
iii) Technologies provide present and future processing technologies for the components and
iv) Processes providing the necessary equipment and design for the technologies.

Applications

Photonics in ICT: Novel components, materials and advanced integration technologies for the optical wide-area, access and home networks will enable efficient exploitation of available bandwidth, low-cost network operation, and data security. Optical interconnects will play a key role for future short-haul data communications and all-optical switching fabrics in e.g. data centers. Green photonics for datacenters: lower power, higher speed; 5G networks using beam steering for higher bandwidth, lower power. Microwave Photonics will provide innovative solutions here.
Photonics for Horticulture and Agro-Food: Growth stimulation by new lighting architectures in greenhouses, photonic sensors for monitoring of climate and growth conditions in greenhouses, photonic trace gas detection for monitoring of crop conditions in the field and in stores. Monitoring of soil conditions (fertilization) and salt-fresh water ratios. Quality monitoring of packed nutrition and fruit. NIR spectroscopy to measure nutrition in crops before and during harvesting, milk analysis for food safety.
Photonics for Water : Photonic sensors for water quality control in distribution networks and reuse facilities and for structural integrity monitoring in large constructions like dikes, bridges and flood control dams. Photonics technology will be used for real time monitoring of water movement, sediment transport and offshore structures e.g. windmills.
Photonics for Energy: Solar cells, solar fuel, energy saving lighting systems, green ICT using energy saving photonics in data transmission and switching, photonic monitoring of mechanical stability in windmill propeller blades.
Photonics in Healthcare and Life Sciences: Medical devices including medical therapeutical systems and systems for in vivo and in vitro diagnostics. Major products include endoscopes, therapeutic laser systems, medical imaging systems, CR systems, ToF-PET and PET-MRI, fluorescence diagnostics systems, coherent detection, optical coherence tomography systems, SPECT, Raman (CARS) based diagnostic systems, Photo Acoustic imaging technologies. All systems comprise a combination of photonic components (lasers, detectors), micro-electronica, mechanics and software. Miniaturization of these systems is often desirable to bring these technologies from the clinic towards the practitioner/patient. Medical technology with non-invasive monitoring (through skin with light – spectroscopy) and minimal invasive surgery (fiber probes).
Photonics in Security, Metrology and Sensors: Enhanced sensitivity operation, single-photon detection. Self-sustaining sensors with low ultra-low power consumption. New sensing functionalities, including unexploited wavelengths, active vision, 3D-Vision. The ability to operate sensors in all ambient conditions, including lighting, temperature, pressure, humidity. New applications in the soft X-Ray, VUV and EUV wavelength region (<200 nm) as well as infrared, > 2µm for gas detection). Environmental

monitoring Air and water quality, DOAS (Differential Optical Absorption Spectroscopy) for measuring air pollution. The combination of Integrated photonics based fiber optic sensing and datacom for smart and high performance sensing concepts.

Photonics in Manufacturing: New manufacturing processes and process monitoring with extraordinary quality that will allow mass customization, rapid manufacturing, non-destructive testing via THz imaging and zero-fault production.

Photonics in Automotive: With a focus on intelligent electromechanical systems, the photonics based sensor technology will be integrated in mechanical parts requiring robust components for in-car communications, monitoring, warning and vision.

Photonics in Aerospace: New optical equipment using e.g. radar, LIDAR and space communication. Including Integrated photonics based smart, redundant and reliable sensing fiber optic systems for extreme harsh environments.

Photonics in Big Science: We seek integrated design for cutting cost and improving performance of high resolution imaging instruments from the innovation phase to conceptual prototype design. Existing telescopes: WEAVE, 4MOST, MATISSE, HARPS3, ALMA receivers, New 40meter telescope E-ELT: METIS, MICADO, MOSAIC, EPICS, Technology development: CRiSP, Immersed Gratings, Active optics, cooling, nm control, detectors (NOVA).

Components + Systems

Photonic components and systems span a broad frequency range from high energies (EUV) to low energies (THz) and can be divided in the following four main functions. However, in most high-tech applications a combination of these functions is present.

Generation of Light: Sources include integrated lasers, solid state green LEDs, photonic crystal lasers and materials for light conversion (such as phosphors and quantum dots), CMOS and other single photon technologies, quantum cascade lasers, VCSELs, plasma sources, ultra-short pulses, high power lasers, THz sources, nano- and, non-linear optical sources, free-electron based sources, broadband VUV sources, fast tunable nanosecond lasers and new scintillation materials. Work on sources includes improved emission by engineering of optical density of states and/or scattering structures, and by improved excitation mechanisms.

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

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

Light detection: Novel types of spectroscopy and microscopy, also with sub-diffraction limited resolution, (remote) sensing, new imaging systems, highly efficient light harvesting structures, optical antennas, optical signal processing, near-field detection, interferometry and metrology, single photon and plasmon detectors. Integrated photonics based spectrometry and interferometry detectors for high sensitive measurement performances, extreme low-noise detection.

Displays: 2D measurements of displays.

Technology

Photonic integration: Includes the development of generic integration platforms and foundry models. Addressed technologies comprise III-V semiconductors e.g. InP, TriPleX and SOI, CMOS post processing; assembly, alignment and fixation, RF processing in optical domain (microwave photonics). Also photonics technology will be combined with e.g. fluidics and mechatronic technologies.

Photonic-electronic integration : At the chip, board and system levels. Hybrid- and heterogeneous integration. Si-III/V integration; process control/improvement; assembly technologies; pick-and-place tools, optical PCB.

Packaging technologies: Packaging and assembly technologies for low cost sources and detectors, flip-chip optical coupling, combined glass and non-hermetic packaging. Assembly equipment for prototyping of bulk optics with high tolerance requirements. Automated equipment and processes dedicated to wire-bonding and fiber-coupling for series production.

Free space and micro optics: Architecture and assembling of optical components into an advanced photonic device. This includes remote solid state lighting, photovoltaics, microscopy, advanced spectroscopy, health instruments and lithography. 3D printing of high quality micro optical components.

New materials: Includes semiconductors, glasses, plasmonic materials, metamaterials, photonic crystals, nano- (plasmonic) structures, quantum dots, nano-crystals, nonlinear materials, doped materials, magneto optical, electro optical and random materials, organic materials, organic-inorganic combinations and new bio materials.

Processes

Equipment: In order to manufacture photonic components and integrated devices, development of new process equipment for front-end and back-and manufacturing and testing may have to be developed. This includes new assembly and packaging processes for 2D and 3D assemblies towards volume production, including novel interconnection techniques for photonic interfaces. Packaging and assembly technologies for low volume, high end optics and micro-optics need to be developed as well.

Manufacturing and prototyping: The need for cost effective photonic devices drives the need for (standard) technologies for cost-effective high speed manufacturing of these components and subsystems including packaging and assembly processes for volume production and photonic prototyping. This includes standards for generic processes and design rules for assembly of photonic sub-systems, i.e. photonic integrated circuits. Fast time to market is required.

Simulation and design tools: New simulation and design tooling must be developed enabling the designs of new devices and circuits, and link the tooling with the new integration technologies and the manufacturing and prototyping processes (validation). The overall quality of the supply chain will increase by putting more “feedforward” into these tooling, building a living database for further improvements of this supply chain, products and processes.

Core and disruptive technologies: Research at the photonic groups of our universities have next to public private partnerships also projects on fundamental properties of materials and processes involving the future implementation of the outcome. It includes application-specific components and systems such as laser and other light sources, imaging units, transmitters and receivers, detectors and sensors and hybrid integration. Disruptive technologies often exploit effects at the limits of photonic interactions, including nanophotonics, sub-wavelength and near-field effects, plasmonics and quantum effects. Other areas include wave front shaping, ultrafast pulse shaping, nano-biophotonic techniques, security, quantum protection and physically unclonable functions, exploiting scattering of light, chemical imaging/

nonlinear optical imaging / multimodal imaging, chemical microscopy / nonlinear optical microscopy / multimodal microscopy, novel and advanced coherent light sources (nonlinear and laser sources), extreme nonlinear optical frequency conversion on-chip, all-optical switching on-chip , control of spontaneous emission, e.g., in photonic media, photonic metamaterials, nano-plasmonic/nanophotonic devices, advanced frequency conversion techniques, transport of light in periodic and random media, advanced modeling of complex wave propagation (e.g. finite elements).

3 Priorities and implementation

3.1 Implementation in public-private partnerships and ecosystems

Priorities for Photonics for ICT

The Netherlands is very strong in research in the technologies which underpin photonic ICT, but ICT solutions 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, there is a real opportunity for Dutch companies to operate over the full value chain. On the counter-side, not doing so leads to a risk that expertise clusters outside the Netherlands, operating margins are reduced, and international competition will grow further in the areas where the Dutch currently excels. A number of recommendations are made:

- Bridging the gap between lab-proven concepts and viable product is critical. Highly innovative circuits and concepts are developed at the Technical Universities and the national research institutes, but the support to take this through to field-deployed prototype is still in an early phase.
- Changing the mind-set for systems innovators and original equipment manufacturers, encouraging the inclusion of innovative new solutions within product lines rather than buying in off-the-shelf solutions will lead to synergistic benefits and competitive advantage.
- World-leading concepts in photonic integrated circuits are developed in the Netherlands, but further support is needed to bring these through to the industry, assisting companies with the up-skilling of the work-force and providing access to manufacturing technologies which can be deployed in future product lines.
- Creating regional hubs and ecosystems to develop innovative new photonic ICT solutions. This extends beyond the photonic technologies to include the technologies which they are connected to. The high speed electronics, the mechanical assembly systems, the precision control systems.
- Innovations are required in assembly technologies to enable competitive advantage with respect to low-wage economies. Photonics markets contrast to electronics markets in that they are high value with comparably low volume, and this has driven significant assembly work to low-wage economies. The migration of manufacturing technologies is commonly followed by a migration in the research and development base, but a paradigm shift in the cost model for hardware assembly can also lead to the re-shoring of manufacturing.
- The development of wafer scale processing for both optics, and also for smart systems incorporating combinations of optics, photonics and electronics.

Priorities for Photonics for Industrial Manufacturing & Quality

- **Excellence for 'design to part' in photonics manufacturing**: This research topic addresses the complete process chain of "Additive Manufacturing" from CAD model to the product. Although methods of additive manufacturing have already demonstrated enormous potential for future applications – and have already begun to penetrate certain niche applications - there is still significant 'unknown land' to explore. What is clear today is, that a deeper understanding is necessary at all stages of the process chain, in order to enable the full future innovation potential of these revolutionary techniques.

- 'Photon-induced surface processing – laser engineered surfaces' is a cross-cutting key enabling technology, as it effects numerous applications in fields as relevant as health, mobility, energy generation and resource efficiency. Examples are the generation of large area micro and nanostructures or the functionalization of surfaces for corrosion resistance, anti-fouling, optical or biological functionality and modification of magnetic and electric properties. Photon-induced surface processing will not only replace other technologies but will also enable completely new functionalities. Basic technologies are developed for photonic treatment of surfaces and first applications are established. This activity shall support the exploitation of laser surface processing for the enormous number of new applications. Only a very small number of large scale laser surface processing has found its way to manufacturing today. In terms of the competitiveness of Dutch industries, the proposed research action on photonics manufacturing in the Photonics21 multi annual roadmap will have a major impact on maintaining the industrial laser processing technologies.

Priorities for Photonics for Health

- Main focus of photonics research in life science and health must be on realizing novel techniques and devices that can contribute to the societal themes. This requires a shift in focus from high-end academic problems and systems where cost of the product does not play a primary role, to small and cheap devices that solve problems in primary care and home care. One should not exclude research on high-end applications, such as molecular imaging, but focus on the current research financed with public funding on the hottest societal challenges.
- To be successful, work should be carried out in teams in which the entire knowledge chain is present: from primary care professional to medical and biomedical optics scientist to photonic component developer and medical device expert and finally business developer. Currently much of the biophotonics work is already done in multidisciplinary teams, but one needs to work in teams of a much broader spectrum. In addition, such teams should be problem oriented, trying to find the best technology for the medical problem, rather than technology oriented. Furthermore, one must realize that creating a successful novel product in a clinical market requires more than just device development. So not just the team but also the work is multidisciplinary. As a consequence, funding agencies should develop dedicated funding programs that can handle such programs.
- The life science and health field will generate an increased demand for miniaturization and integration of photonic solutions into small and cheap devices. Component developers should be prepared for a variety of requests from the life science and health field that will most probably share many common requirements. Development of standardized approach may accelerate application developments.

Priorities for Photonics for Security, Metrology & Sensors

- Efficient processes in the chemical and food industries need sensitive and highly reliable instruments for online and inline process control and analysis. Due to its inherent advantages photonic instrumentation establishes a large and most rapidly growing market compared to other measurement techniques. Process Analytical Technology (PAT) starting from a FDA initiative in 2004 and initially focusing on the pharmaceutical industry has become a major toolbox to achieve highly efficient processes worldwide. Nowadays, PAT aims at a complete understanding and modelling of production processes which creates additional demand for suitable instrumentation.

- Sensing for safety and civil security: Breakthrough advances in cost-effective, high-performance, multi-band optoelectronic devices (including sources) for near- and mid-infrared sensing applications (spectral range of 0.7 to 50 µm) representing high-volume markets. Device cost in volume production should not exceed 10 times the related cost of devices for the visible domain.
- Disruptive approaches in sensing: Proof-of-concept for photonic sensing devices offering breakthrough advances in sensitivity or specificity enabled by new technology, new device concepts (e.g. based on integrated photonics, quantum optics or quantum technologies, plasmonics, metamaterials, or non-conventional wave front shaping), new materials or non-conventional light-matter interaction from the research lab. Actions should demonstrate the feasibility of industrially relevant devices through a functional prototype.
- New production methods for medium and high volume quantities: miniaturization and affordability of the measurements are demanding technological breakthroughs. Better mobility and further miniaturization will allow more applications in the field. The effects of miniaturization are threefold. Firstly, smaller devices enable local measurements in confined environments and can be configured as an array of relative simple sensors in a network. Secondly, the devices are portable and can therefore be used on the spot anywhere where needed. Finally, the miniature devices open the door for drastic cost reductions and volume production. These three effects reinforce and will create new volume applications and markets

Priorities for Photonics for Design and Manufacturing of Components and Systems

- Photonic Integration, with emphasis on generic integration technologies. In this emerging field with a high growth potential, which is listed as a first priority in the European roadmap, the Netherlands has built a leading position in two of the three major integration technologies, InP and TriPleX technology, and is a player in the third one: Silicon Photonics. Generic integration technologies enable development and manufacturing of complex integrated systems at strongly reduced cost. Europe has taken the lead in this technology, and the Netherlands is playing a central role. The Dutch position should be further strengthened by stimulating the full ecosystem, including generic foundries, photonic design software companies, design houses, packaging providers, research institutes and last but not least, potential users of this novel technology.
- Novel and enhanced spectroscopy technologies. Spectroscopy is already used widely in production and product control. Novel concepts like CARS (coherent anti-stokes Raman spectroscopy) or LIBS (Laser Induced Breakdown Spectroscopy) will soon make their entrance in the factory. New miniaturizing concepts for spectrometers will also allow for a wider adoption of these techniques.
- Integration of photonics with microelectronics, on the system, board and chip level. The Netherlands has a strong position in microelectronics and advanced packaging and assembly technologies. This position should be used for building a lead in advanced integration technologies, such as 3D integration of electronics and photonics, including wafer scale technologies.
- Technologies for cost-effective manufacturing of components and subsystems, including automated photonic device assembly and electro-optical circuit board technology.
- Exploitation of novel materials and device concepts, relying on carrier or photon confinement at the nanoscale and providing improved performance or functionality. Examples include quantum dots,

nanowires, photonic crystals, plasmonics and meta materials. Approaches for cost-effective manufacturing of nano photonic devices should be explored.
- Development and evolution of robust, accurate and efficient simulation and computer aided design (CAD) tools, including integration of optical circuit design with system-level simulation. Use established standards for design flows, process design kits and 2.5D / 3D integration structures. Move from 'standalone concept's to integrated design environment, handling simulation, design, mask layout, design rule checking and related aspects, where new capability is added as 'plug-in' rather than incompatible software.
- Devices for application in high speed optical links and network and energy efficient scalable photonic switching & interconnect.
- The consortium GPICSFab has been established to stimulate joined operation in the supply chain of integrated photonics by sharing test, fabrication and production resources, activities and experiences for the purpose of connecting industrial needs, research and education.

3.3 Linkage with other instruments that stimulate innovation

- The Eindhoven University of Technology has initiated: Photon Delta: the photonic ecosystem in and around Eindhoven. The focus is to bring photonic chip developed at the TUEindhoven into an industrial ecosystem of companies active in design, processing, packaging and commercialization. This will become a hotspot for Photonics and is supported by local industry, university, Brainport Development, Brabantse OntwikkelingsMij and Province Noord Brabant.
- Photonics is a driving force in the fundamental research programs of NWO, and the EU programs Horizon2020 and ECSEL with their specific photonic calls and increased budget. Applied photonic research, in which fundamental research results are transferred to applications within collaborations between industry and knowledge institutes like AMOLF, ASTRON and SRON, will increasingly be executed within the framework of these programs.
- 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.
- During 2016 and 2019 follow up programs in Topconsortium Kennis & Innovation (TKI's) will be initiated based on the roadmap. The PhotonicsNL association will give support with the following activities: setup, maintain and develop the Photonics roadmap; strengthen and maintain national and international contacts; promote Holland Photonics at national and international exhibitions and conferences. The Memphis consortium will coordinate and initiate new collaborative projects.
- Education: SMEs lack sufficiently educated employees skilled in modern photonics and test equipment. Participation of e.g. HBO, WO and graduate schools in collaboration with projects will stimulate students in this field. Support of setting up curricula on photonics at all levels, including business development (Bachelor, Master and Graduate Schools) has a high priority. International collaborations are foreseen (e.g., Belgium, France, Germany, UK).

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

The Netherlands is in an unique position to collaborate with world leading groups at Universities and Institutes actively researching each of the topics mentioned in 2.3. The academic research in supported by Dutch industrial photonics research and development in large companies (e.g. Philips and ASML), Dutch SME's and Institutes such as TNO ASTRON, NOVA,SRON and VSL will be continued. The Dutch photonics community is very active and successful in H2020 program and many projects are foreseen in the next years.

4 Partners and process

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

Today over 120 Dutch industrial and scientific partners are active in Photonics.
Industrial input to the roadmap has been requested from:

ACAL, 4PICO, Adimec Advanced Image Systems B.V., ADMESY BV, ALSI International, ANTERYON BV, ASML, ASML, ASTRON, Avantes BV, AWL Techniek, Bright Photonics B.V., Cosine Research B.V., Teledyne Dalsa, Demcon Twente B.V., DiagnOptics Technology B.V., Diamond-Kimberlit, EFFECT Photonics, Element Six BV, Eurofiber, Flexible Optical B.V., Genexis B.V., Hybriscan bv, IAI industrial systems, IMMUNICON EUROPE, Innoluce bv, Iris Vision, Janssen Precision Engineering bv, Lambert Instruments, Laprocon bv, Laser 2000 Benelux, Laser Application Centre, Lens R&D, Lightmotif bv, LIONIX BV, Lumileds BV, Luminostix BV, LuXEcel, MA3 Solutions, Maastricht Instruments bv, MACH8 Lasers BV, MECAL, Micro Lasersystems BV, MILABS BV, NEDINSCO BV, Next Scan Technology bv, NTS Systems Development BV, O2View, Ocean Optics BV, Octoplus BV, Oldelft B.V., Optisense B.V., Philips Research, PHOENIX BV, Photonis Netherlands BV, Quest Innovations, RiverD International bv, Satrax bv, Sensata Technologies Holland B.V., Sensor Sense B.V., SMART Photonics B.V., SST, TE Connectivity, Te Lintelo Systems BV, Technobis bv, Thales Nederland BV, TNO, TNO & Holst Centre, Vadeno Nederland, vanderHoekPhotonics, Vision Dynamics Group, OGS Systems, VOS Instrumenten b.v., VSL, VTEC Lasers & Sensors, WimOptik, XIOPhotonics

Input to the roadmap form academic partners active in photonics has been requested from:
AMOLF, ARCNL, ASTRON, EMC, KUN, NOVA, RUG, RUL, LUMC, RUL, SRON, TUD, TUE, UMCG, UT, UU, UVA, VU.

4.2 Process followed in creating/maintaining this roadmap, including role of SME

The first original version (2012) of this roadmap was made based of a large number of contributions from industry, academia and institutes, including SMEs. This 2015 version builds upon the original as well as the 2013 and 2014 updates.
Parallel to updating the 2015 version of the HTSM photonics roadmap, a Strategic Research Agenda was prepared in the framework of a EU CSA project "Innopho21" in which Photonics Cluster Netherlands – today PhotonicsNL - was a partner. This SRA will soon be published. In order to compare the national and international photonics SRA, the Photonics21 classification of the various topics has been used but is fully compliant with the Dutch classification in the topsectors. E.g. solar, lighting and photonics have different roadmaps in the Netherlands but are all addressed in WG4. Life Sciences & Health is a topsector and Healthcare is a roadmap in HTSM both addressing photonic solutions.

This HTSM photonics roadmap builds on the input provided by the members of the working groups of the SRA.

In the update of the photonics roadmap with new topics and industrially relevant long term potential collaboration, invitations for input were sent out to 60 academics active in photonics and 78 industrial partners (70 SME's) including TNO (see section 4.1). Their feedback is included in this version.

The editing of the roadmap is carried by PhotonicsNL / Bart Verbeek and in collaboration with the roadmap responsible Hans van den Vlekkert – LioniX bv.

5 Investments

Public-private partnership R&D budgets

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

Tabel 1

Roadmap k€	2015	2016	2017	2018	2019
Industry [1]	4.700	3.550	3.100	11.200	10.500
TNO [2]	4.000	4.250	4.250	4.100	4.300
NLR					
NWO	4.600	3.800	3.800	2.800	1.500
Universities	5.300	5.000	4.250	4.100	4.100
Dept./Regions	175	175	750	750	750
Grand Total	18.775	16.775	16.150	22.950	21.150

Tabel 2

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

Notes
1) Increased numbers for 2018 and 2019 is based on expected industrial collaboration with NOVA.
2) TNO numbers are exclusive Semicon and Space.