TOWARDS 2020 – PHOTONICS DRIVING ECONOMIC GROWTH IN EUROPE

Multiannual Strategic Roadmap 2014–2020

PHOTONICS21

Imprint

Towards 2020 – Photonics Driving Economic Growth in Europe

Multiannual Strategic Roadmap 2014 – 2020

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Executive Summary

The rise of photonics in Europe from a niche activity to a Key Enabling Technology, and on to becoming one of the most important industries for the future, shows how photonics is on its path to making the 21st century that of the photon.

Photonics is everywhere around us: from communications and health, to materials processing in production, to lighting and photovoltaics and to everyday products like DVD players and mobile phones. Yet the full disruptive potential of photonics is only now becoming clear. New advances in photonics will revolutionise healthcare and provide new ways of detecting, treating and even preventing illness. In manufacturing, laser processing will be a basic prerequisite for high-volume, low-cost manufacturing. Photonics technology will help overcome the limitations of electronics in computers through all-optical computing or even quantum computing. Photonics will move communications into the terabit era by dramatically increasing data capacity and data transmission speeds, while simultaneously reducing the networks' carbon footprint and the overall cost per bit. Photonics will play a key role in addressing the challenges of energy efficiency and moving to a low-carbon economy. In the future, solid-state light sources are expected to outperform almost all other sources in terms of efficiency, offering potential energy savings of 50% or even more, when used with intelligent light management systems. Sensor applications in smart power grids, smart buildings and smart industrial process control will contribute significantly to more efficient use of resources and meeting environmental challenges.

Through the long-term commitment of all parties to a common shared vision, the proposed Photonics Public Private Partnership (PPP) in *Horizon2020* will lead to a more competitive photonics sector in Europe. Embracing the main recommendations of the Key Enabling Technologies (KETs) initiative, the Photonics PPP will be vital for achieving the critical mass necessary for developing a coherent application oriented and market needs driven technology & innovation, and for strengthening RDI capabilities across the full value chain, from research to manufacturing and from materials to OEMs & end users. It will develop and implement an integrated RDI programme that fully meets the needs and priorities of markets, and tackles the 'valley of death' problem by undertaking strategic projects. Continued close collaboration with member states[1] will be critical for the success of this PPP.

1 through the Photonics21 Mirror Group

Left: Photonics offers enormous economic potential for Europe. © Fotolia

Right: The annual market growth rate of photonics in Europe is estimated at 8-10%. © Fotolia

Underpinning all the proposed activities is the objective of growing photonics manufacturing in Europe and creating further 'high skill' employment. This will be achieved by enabling the photonics products themselves to be manufactured in Europe, and by ensuring the ongoing competitiveness of other key photonics-dependent manufacturing sectors in Europe.

The proposed Photonics PPP will differ from the existing support mechanisms by establishing a closer alignment of industrial and public strategies, and by pooling academic, industry and public resources to provide sufficient know-how and the investment essential for achieving major progress towards this joint strategy. Applying an open innovation process will help achieve the specific aim of the PPP to establish a more effective translation of scientific research into products. In recognition of the importance of forming a PPP, the European Photonics Industry undertakes to make a substantial commitment through a four-fold leverage of public funding to achieve a total investment of €7 billion (€5.6b from the private sector and €1.4b from the European Commission).

Added-value for Europe through strengthened industrial competitiveness

The photonics global market is today around €300 billion. Europe has established a strong position with an overall total share of 20%, and as much as 40% in key sectors such as lighting. The European photonics industry employs about 290,000 people directly, many of these in the over 5000 photonics SMEs. Photonics also has a substantial leverage effect on the European economy and workforce: 20-30% of the economy and 10% of the workforce depend on photonics, directly impacting around 30 million jobs. Photonics also offers solutions which address key societal challenges, such as energy generation and energy efficiency, healthy ageing of the population, climate change, and security.

Photonics is a Key Enabling Technology for Europe. It is a very dynamic and vibrant industrial sector in Europe and holds the potential for huge market growth. The expected compound annual growth rate for photonics over the coming years is 8%[2], clearly demonstrating the rapid growth of this key technology sector. In specific areas, substantially higher growth rates are predicted, for example, in green photonics[3] the expected CAGR value is nearer 20%[4].

Photonics has a substantial leverage effect on the European economy and workforce.

Photonics is a Key Enabling Technology for Europe.

2 http://ec.europa.eu/enterprise/sectors/ict/files/kets/photonics_final_en.pdf

3 Green photonics comprises photonics solutions that generate or conserve energy, cut greenhouse gas emissions, reduce pollution, yield environmentally sustainable outputs or improve public health.

4 http://ec.europa.eu/enterprise/sectors/ict/files/kets/photonics_final_en.pdf

Photonics – speed for the European economy. © Fotolia

Europe now needs to build further on its strong position in the global photonics markets, and it will be crucial to align and coordinate this highly multidisciplinary and fragmented field. It needs to strengthen its industrial leadership by promoting wide-scale cooperation and greater integration across the whole research and innovation value chain, from advanced materials to manufacturing, and from advanced research to technology take-up, pilot lines and demonstration actions. A Photonics PPP is seen as the optimal vehicle for achieving this development.

Particular emphasis needs to be given to supporting the innovation of the large number of SMEs active in this area and helping them grow further to become global players.

Main activities for the Photonics PPP

The dual challenge facing Europe is both to lead in photonics technology innovation, and to exploit these results though successful commercialisation. In this way, the goals of solving the grand societal challenges and of generating sustainable economic growth in Europe can be met. By implementing this strategy, the 21st century can truly become the century of the photon.

The potential Research and Innovation activities best placed to address these challenges and objectives are:

- **Disruptive and road-map based core photonic technologies**
  - **Roadmap-based research** will be undertaken to drive technological development and innovation in strategic application areas where Europe is strong. These strategic application areas include optical data communications, laser manufacturing, biophotonics for medical and biomedical applications, imaging and sensing for safety, security and the

environment, and lighting. The emphasis will be on broader cooperation across the whole research and innovation value chain and the close involvement of end-users, including citizen groups where appropriate.

- **Disruptive technology** breakthrough advances in nanophotonics, quantum information, extreme light sources, etc., will be pursued, complementing the roadmap-based research, and bringing the potential for disruptive innovation in support of future European leadership.

Demonstration

Specific deployment programmes using photonic innovations will be needed to demonstrate social innovation and leverage EU infrastructure to create jobs. Such infrastructural projects could provide benefits to all 500 million people in the EU, and not solely to those directly involved in the photonics industry. Deployment programmes would be focused on life cycle and applications.

In this way, coordinated market pull/push measures will seed and then accelerate market penetration, ultimately leading to wider technology adoption and consequent job creation. Measures would include the launch of high-visibility, demonstration projects that provide the European photonics industry with a first-mover advantage in the global market.

Photonics Manufacturing Platforms

Underpinning all the proposed activities is the objective of growing photonics manufacturing in Europe and creating further high skill employment. This will be achieved at two levels; enabling the photonics products themselves to be manufactured in Europe, and ensuring that other key manufacturing sectors in Europe, dependant on photonics technology, can remain competitive. To this end the following measures would be implemented:

- Improvement of the infrastructure for photonics manufacturing in Europe. This involves making full use of the existing manufacturing excellence of research institutes for supporting industry, especially innovative SMEs. The creation of such generic photonic foundries, based on public-private partnership, will enable cost-effective and widespread deployment of photonics technology in numerous applications, and ultimately lead to volume production.
- Establishment of pilot production facilities, in which industry and research institutes can jointly develop innovative photonics production processes, targeting applications relevant to societal challenges and economic growth.

Since the value chains in specific photonics application areas in Europe are fragmented across different member states, demonstration activities and manufacturing platforms are expected to reinforce the innovation ecosystems at local (smart specialisation) and European levels.

Innovative photonics SMEs

SMEs lie at the very heart of the European photonics industry, and play a major role in driving innovation and economic growth. It is essential for the future prosperity of the European photonics industry, and thereby of European society, that their competitiveness in the global market is sustained and grown further. Take-up of and RDI support for innovative photonics technologies through ‘light touch’ open schemes will be promoted. The emphasis will be on strengthening the competitiveness of European SMEs, and on the creation of new business opportunities.

To this end, a fast-track funding vehicle for photonics SMEs is envisaged within the Photonics PPP. Further synergies with regional innovation clusters will be established to promote SME

Photonics has a critical role to play in addressing key societal challenges.

development through, for example, establishment of open innovation models along the value chain. This would allow SMEs to operate within a streamlined, more market-oriented set of rules, allowing prototype development for shorter-term commercialisation, rather than being limited only to precompetitive R&D.

- **Strengthening Photonics Foundations**
  The actions of the Photonics PPP will be accompanied by measures on education, training and skills development, as well as standardization, international cooperation & outreach. Both industry and academic partners of the PPP will undertake these actions to secure the future work force for this growing industry.

All activities will be accompanied by measures to better attract sufficient capital and management support for seeding and growing innovative business ideas.

The PPP will work towards the establishment of a dedicated European industrial growth fund, leveraging existing investments in photonics innovation through to commercialisation.

Photonics for the Societal Challenges
Photonics has a critical role to play in addressing several key challenges identified by the Europe 2020 strategy.

- In **healthcare, demographic change & well-being** photonics will provide new ways of detecting, treating and even preventing major diseases at the earliest possible stage, improving patient survivability and drastically reducing care costs.
- In **climate action, resource efficiency & raw materials,** new laser-based photonic manufacturing technologies will stimulate new manufacturing processes with extraordinary quality

Creating new business opportunities is key to growth in Europe. © Fotolia that will allow mass customisation, rapid manufacturing and zero-fault production. Photonics will also stimulate the lighting transition from incumbent technology to a low energy consumption, digital technology, built around LEDs, OLEDs, sensors and microprocessor intelligence, contributing to saving energy and money, and increasing visual comfort and well being.

- For **inclusive, innovative and secure societies,** photonics will increase information access for all citizens, through the development of the future Internet infrastructure with multi-terabit capacity, while reducing the networks' carbon footprint and the overall cost per bit. Such Internet infrastructure will leverage the development of new products and sophisticated applications services that fully exploit this connectivity, with huge potential impact on European society in all areas of human activities. Photonics based sensing and imaging will enable higher levels of security and safety through the use of sophisticated surveillance technology and detection of unauthorised goods, as well as contributing to a greener environment through providing advanced pollution detection.

The Photonics PPP will work closely with other players involved in addressing these societal challenges, in particular with Smart Cities, Active and Healthy Ageing, and Resource-Efficiency.

Implementing the Photonics PPP Multiannual Roadmap

Implementing the Photonics Multiannual Roadmap, which has been widely endorsed by the Photonics community in Europe, will be the key objective for a Photonics PPP in *Horizon 2020*. The roadmap recommends that Europe needs to strengthen its ability to make the critical transition from successful innovation in photonics to the industrial deployments necessary for job creation. Bridging this gap must be a key objective of the Photonics PPP. For photonics to yield its full potential as an enabling technology, it will be critical that the inherent synergies within the sector are exploited through integrated research aimed towards identified market solutions, rather than towards isolated components or applications.

Finally, it is recognised that disruptive photonics research is of major importance for maintaining its long-term competitiveness. Therefore, photonics disruptive research, and in particular, research into Organic and Large Area Electronics, will play a significant role within the PPP.

Energy-efficient lighting contributes to a sustainable environment. © Fotolia

Introduction

The preparation of the Photonics Multiannual Strategic Roadmap has been driven by the European photonics community and the European Technology Platform Photonics21 to foster the set up of a Photonics Public Private Partnership (PPP) within the new Framework Programme ***Horizon 2020***. During the roadmapping process, the photonics community and the Photonics21 Work Group Chairs engaged in a close dialogue with the European Commission Photonics Unit of DG Connect.

The Photonics Strategic Multiannual Roadmap is the result of extensive brainstorming and discussions with more than 300 experts from the European photonics community. They have identified strategically important photonics research and innovation challenges as well as crosscutting Key Enabling Technology issues, and have outlined the need for Europe to invest further in these identified application areas and photonics technologies.

The scope of the Photonics Multiannual Roadmap is to provide photonic solutions to the major socio-economic challenges of Europe, such as to the ageing society, health, energy-efficiency, food safety and security. Furthermore, the European photonics community aims to implement the long-term photonics research and innovation strategy elaborated in this Multiannual Roadmap.

As an introduction to the Photonics Strategic Multiannual Roadmap, chapter 1 provides the main strategic objectives and outlines the vision of the European photonics community for future photonics research and innovation (section 1.1). This is followed by a discussion of the proposed Key Performance Indicators that will be used to measure the success and impact of European research and innovation funding under the new Framework Programme *Horizon 2020* (section 1.2). Finally, the introduction outlines the role played by photonics innovation ecosystems in Europe. (section 1.3).

Chapter 2 of this report, *Photonics Research and Innovation Challenges*, outlines the specific research and innovation areas envisaged by the seven Photonics21 Work Groups within the framework of the Photonics PPP. Each Work Group has defined relevant research and innovation areas, and has also produced a series of roadmap tables for the full planned duration of *Horizon 2020*, covering 2014–20.

Finally, to conclude the Photonics Strategic Multiannual Roadmap, chapter 3 outlines the expected impact and benefits of a Photonics PPP for future photonics research and innovation in Europe. Details of the consultation process used to construct these technology roadmaps are presented in Appendix 1.

1.1 Strategic Objectives and Vision

Today, the global market for photonics is estimated to be approximately €300 billion, and the leveraged impact of photonics in other enabled industries is substantially greater in terms of turnover and employment levels. This market is expected to grow significantly over the next few years, with the estimated market size approaching €480 billion by 2015.

Europe has an overall share of 20% of this global market, which corresponds to approximately €60 billion. The European market share rises to as much as 45% in certain specific key photonic sectors, such as lighting, for which many market-leading industrial players are located in Europe. Europe also has particularly strong positions in industrial laser technologies, information and communications technology (ICT), and biophotonics.

The annual market growth rate of photonics in Europe is estimated to be between 8–10%, which is 2–3 times faster than the overall European GDP growth. In specific areas, substantially higher growth rates are predicted, for example, in *green photonics* the expected CAGR value is nearer 20%. *'Green photonics'* is the term used to encompass the application of photonics technologies that can generate or conserve energy, cut greenhouse gas emissions, reduce pollution, yield environmentally sustainable outputs, or improve public health.

The European photonics industry currently employs about 300 000 people in Europe. As the photonics sector is largely based on SMEs (there are about 5000 photonics SMEs in Europe), growth in demand is known to create proportionally more jobs than would typically be seen in a sector made up primarily of big companies.

Funding along the full Innovation Value Chain in Europe

Europe performs a major proportion of the world's research into basic photonics and achieves excellent R&D results, providing Europe with a world leading position. However, Europe needs to strengthen the industrial deployment of these research results by promoting wide-scale cooperation and greater integration across the whole research and innovation value chain. Therefore, it is necessary to rebalance the funding within the new Framework Programme *Horizon 2020*, so as to provide an increased budget of funding to applied research and demonstration programmes for photonics.

The European photonics industry must now continue working with the European Commission and national policy makers to coordinate a joint approach to innovation, and to pool investments for enabling the rapid development of new products and minimising times to market. This speed

The European photonics community defines their vision for future photonics research and innovation. © Fotolia

Left: Europe has an overall share of 20% of the global photonics market. © Fotolia

Right: The European photonics industry currently employs about 300 000 people in Europe. © Fotolia

to market approach needs to include the entire value chain, from advanced research through to technology take-up, pilot lines, and manufacturing platforms.

Bridging the gap between excellent research results and product development, and thus overcoming the so-called *Valley of Death*, must be the key element of a photonics strategy for future research and innovation funding in Europe. This funding approach should be implemented within the new Framework Programme *Horizon 2020*.

Integrated approach to bridge the Innovation Gap

The European photonics community proposes a multiple approach for how the *Valley of Death* problem can be overcome and the innovation gap bridged. Actions are required in the following areas:

- **Disruptive and roadmap-based core photonic technologies**
  - Roadmap-based research with a value chain approach
  - Recognised value of potentially disruptive innovations
  - Early involvement of end-users
- **Demonstration programmes**
  - Deployment programmes to create new jobs in Europe
  - Showcase public authorities' commitment to invest in photonics
  - Accelerate market penetration
- **Manufacturing Platforms to maintain manufacturing in Europe**
  - Improve infrastructure for photonics manufacturing
  - Establish public-private pilot production facilities for industry and research institutes
  - Reinforce innovation ecosystems at local and European levels
- **Innovative Photonics SMEs**
  - Fast-track funding to foster prototyping & short-term commercialisation
  - Reduced administrative burden for SME participation
- **Support Actions**
  - Develop a highly skilled workforce
  - Photonics education, training & skills development
  - Outreach activities to promote photonics to education providers
  - Standardisation

To support this value chain oriented approach, three additional drivers are identified that would greatly enhance its effectiveness:

- The European Commission identified photonics as being one of the Key Enabling Technologies (KET) for Europe. The European photonics community firmly believes that *Horizon 2020* should have a clear focus on this KET to ensure a critical mass of funding budget is achieved.
- Access to venture capital and dedicated SME support should be facilitated within *Horizon 2020*.
- The new Framework Programme should be simplified significantly for greater flexibility, so that the administrative burdens, particularly for SMEs, associated with proposing and participating in a project can be minimised.

Photonics Public Private Partnership in *Horizon 2020*

The photonics community is ready to invest in Europe's long-term competitiveness and growth, and to provide a four-fold leverage of the European funding through private investment. This would sum up to an overall amount of approximately €7 billion.

The photonics community strongly favours a Photonics PPP that would result in a long-term funding commitment, and would be set up as an equitable partnership between the European Commission and the photonics community. To turn this Photonics PPP model into reality, the photonics community asks for lean, simple and efficient structures and procedures. A Photonics PPP structure under *Horizon 2020* should build upon the success of the European Technology Platform Photonics21, with its reputation and established transparent decision-making procedures. Furthermore, the Photonics PPP should not lead to the disruption of the Photonics community in Europe that has been built up successfully over the last 7 years.

Additionally, the European photonics community undertakes to measure the success of the Photonics PPP by Key Performance Indicators.

1.2 Key Performance Indicators

Throughout the course of the *Horizon 2020* programme and the operation of the Photonics PPP, a key feature will be the long-term industry commitment to assess and quantify the level of investment occurring in the field of photonics research and innovation in Europe.

Specifically, the European photonics industry's undertaking to leverage the initial European Commission public funding investment in Europe by a factor of four will be assessed. This commitment will be based on the aggregate performance of the photonics industry partners, rather than that of individual companies. For this assessment, Photonics21 proposes to monitor all companies that participate in *Horizon 2020* Photonics PPP projects between 2014 and 2022.

The photonics community is ready to invest in Europe's long-term competitiveness and growth and to provide a four-fold leverage of the European funding through private investment.

The monitoring would provide a more complete picture of the industry investment of participating companies, and could be confirmed as part of the contract negotiation phase for all industrial participants in new *Horizon 2020* projects. Beneficially, this monitoring of all participating companies will also facilitate the generation of valuable sub-sector specific data.

As their primary Key Performance Indicator, each participating company would provide one overall figure, summarising their company's investments in the photonics area. An accounting firm or similar professional service would perform the monitoring, thereby ensuring a clear commitment to confidentiality, and being demonstrably independent of either parties in the Photonics PPP.

In addition to monitoring direct company investment, an independent macroeconomic study would be conducted on an annual or biannual basis. Photonics21 proposes that an independent organisation will conduct this macroeconomic study to monitor the overall impact of the PPP and the state of the photonics sector as a whole. All participating companies would be required to provide information to the organisation conducting the macroeconomic study.

1.3 Photonics Innovation Ecosystems in Europe

The European photonics landscape is made up of high-level research groups and a strong photonics industry, consisting of both SMEs and large companies. Most of these photonic players are active in regional innovation clusters and national technology platforms.

Regional *innovation clusters* are composed of large companies and SMEs, start-up companies, public and private research centres, universities, specialised suppliers, investors, and regional & government agencies within a geographic region. They work together in a partnership to follow a common photonics regional development strategy, devised to create synergies in a specific photonics application area.

European and national *technology platforms* are networks formed between private and public players, working together on common strategic photonics topics to define a common national photonics strategy and promote greater political visibility for photonics.

Distribution of photonics regional innovation clusters and national technology platforms. The administrative centre of clusters or platforms is only indicative of the region and there is significant variation in the geographic coverage of each structure. © Photonics21

Photonic players are active in regional innovation clusters and national technology platforms. © Fotolia

Regional innovation clusters and national technology platforms each represent the interests of the photonics community at a regional and national level. To ensure that photonics becomes part of the regional or national innovation strategies, direct and effective engagement with regional and national governments will be essential. Furthermore, photonics clusters and platforms provide a centre of gravity and a critical linkage between the Photonics PPP and regional activities, and, through this, will help define strategic research and innovation directions at the European level. The development of photonics clusters and platforms is an ongoing processes, and we do expect to cover a 'large area' of EU at regional level and all countries at national level.

The EU acknowledges the importance of national technology platforms and regional innovation clusters for developing further the photonics innovation capacity needed in Europe, and strengthening the innovation value chain. Specifically, these regional structures now have the critical mass to define strategic directions at regional and national level. Consequently, they are expected to play a key role in Smart Specialisation, the EU's strategic approach for Structural Fund investments in R&I, aimed at maximising knowledge-based development potential at the regional level.

It is vital therefore that the photonics regional innovation clusters and national technology platforms continue their cooperation and work together with the Photonics PPP, developing greater community cohesion and pursuing a common photonics R&I strategy on a European scale, with further involvement of new regional clusters and national platforms. In this way, the national technology platforms and regional innovation clusters will provide a critical link between *Horizon 2020*, national and regional strategies, and European regional development funds to define and implement the Photonics PPP strategy and guide R&D funding to innovative European SMEs.

Photonics Research and Innovation Challenges

The following sections have been prepared by the Photonics21 Work Groups. The photonics research and innovation challenges being faced are outlined for each of the different photonics application fields. In particular, discussion is presented of how each field addresses the socio-economic challenges, and of which value chain partners should become involved in photonics research and innovation.

2.1 Information & Communication

Main socio-economic challenges addressed

Severe challenges must now be faced that could have major potential impact on Europe's prosperity and sustainability: ensuring sustainable development, securing energy supply, addressing the needs of an ageing population, and ensuring human and environmental health. In addition to these challenges, a key focus must be achieving secure employment across Europe over the coming years.

Information and communication technologies (ICT), underpinned by optical broadband communication technologies, will address many of these socio-economic challenges. ICT supports and enables new ways of living and managing resources. ICT and related applications will offer new job and wealth opportunities, providing people living in secluded areas the same opportunities as those living in large cities.

Additionally, broadband communication technologies significantly reduce carbon emission, and enable most of the services used within our homes, from education to work, from government to health, from entertainment to security. In most advanced countries, education and technically advanced home-based work environments are enabled through broadband communication services.

We will soon live in a world in which everything that could be connected will be connected. As well as connecting homes, broadband technologies will also connect businesses, equipments and infrastructures for research and production, opening up new commercial opportunities and enabling different ways of living. All these solutions will need photonic systems and technologies, because they are the only possible way to sufficiently reduce energy consumption, whilst still providing the high levels of performance demanded. Photonics is the enabling technology for all wireless and wired broadband technologies.

Demands for connectivity and data are growing exponentially. Moreover, information storage, management and security will require new, dedicated solutions to match these demands. All such challenges will need broadband access to network resources, a high capacity flexible network, and a large number of network environments, such as datacentres, power grids and research infrastructures.

In addition to these challenges, increasing global competition from APAC (China, India) and the US requires greater innovation and more entrepreneurship in Europe to reinforce and grow its leading role. The ability of European industry to customise and provide successful end-to-end solutions, particularly photonic solutions, will be the key to securing future employment for Europe.

Major photonics needs

Photonic systems and networks, architecture and functionalities must undergo significant changes to cope with new applications. With the growing concern about energy efficiency and carbon emissions, significant changes are necessary in all network layers and segments (core/metro/access/datacentre). Moreover, major needs exist to make the networks faster, more secure, more flexible, more transparent, easier to use, and to bring them closer to the customer. Functionalities for which photonics can bring unique advantages, have to be addressed. These will primarily be high-capacity, high-speed and low latency transmission of data between arbitrary end-points, and could also extend into areas such as encryption, switching, quantum communication and computing.

Novel and disruptive techniques are required to cope with the ever-increasing demands for capacity, especially in the backbone networks, for which a transmission capacity of several times 100 Tbps per fibre is predicted by the year 2020. Today the growth in datacentre traffic is demanding more energy efficient ways of computing and moving data across the network. Photonics opens up exciting

Photonics is the enabling technology for all wireless and wired broadband technologies.

The speed of the internet is critical for the future knowledge society. © Fotolia

Optical fibres drive the global network. © Fotolia

A major challenge is the development of high-bandwidth, low energy consumption optical interconnects at low cost.

opportunities for solving the bandwidth limitation of data interconnects at rack, board and chip level. A major challenge for the coming years will be the development of high-bandwidth, low energy consumption optical interconnects at low cost. New services, such as cloud computing require significant improvements in the network architecture and high-speed (fibre-based) access to the customer.

Efficient production of photonic systems and photonic integrated circuits (PICs) is a major need. Significantly more bandwidth is required for next-generation applications in computing and storage, in communication infrastructure, and in the access market. By integrating programmable electronic and photonic circuits in a single package, such optical ASIC or FPGA technology can break through the reach, power, port density, cost, and circuit board complexity limitations of conventional solutions. In this context, an efficient production of PICs will be essential. Photonic integration will play a key role in reducing cost, space and power consumption, and improving flexibility and reliability. Additionally, development of simple and robust on-chip test capabilities and generic packaging and assembly options will be required for achieving cost efficient production processes.

Overall, it is evident that the development and product introduction of advanced photonic technologies will require significantly more financial resources than in the past, thereby exacerbating the risk that, if Europe is unable to raise sufficient budgets, such technologies will move to APAC.

Involvement of value chain partners

The involvement of end-users is extremely important for developing bespoke photonic solutions, which match to the end-users' specific needs. This is especially important, for example, when building new networks such as smart power grids, which are expected to incorporate new technologies and end users, and will be managed and controlled by advanced photonic communication technologies.

This also applies to applications such as the Internet of Things for ambient assisted living or health care services, and in smart city environments. Involvement of the end-users allows for enhanced testing and the creation of new applications and services at early stage. The tight coupling of information and communication technologies in end-user solutions will illustrate effectively the leveraging effect that photonics communication technologies bring to Europe. Focusing on the development of customised end-to-end solutions has the potential of anchoring technology development, growth, and jobs in Europe. It creates additional business opportunities for eco-system partners, focusing on the adaptation of such solutions to varying regional requirements.

Stimulating interaction between research institutes, universities and industry is required to identify applications and related R&D, where photonics can bring unique advantages. Creation of open innovation centres can help to foster this collaboration. Moreover, Europe needs to invest in education and science for developing people and their ideas. Education and advanced training of engineers and scientists is required at a high level to increase the level of innovation in optical communication components, sub-systems, systems and networks. A number of successful European projects have already been instigated in this direction, such as ePIXnet, ACTMOST, and EUROFOS. Institutionalising such interactions within the Work Groups of Photonics21 could provide a sustainable, open, transparent and European-wide collaboration involving all the major stakeholders. Current approaches could be beneficially extended to include direct interaction between the stakeholders, such as concertation, consultation and roadmapping for new research and innovation activities, establishing ad hoc collaborations between members, and exchanges of people and resources. The scope and structure of Work Groups must be sufficiently dynamic to allow for new developments and the incorporation of new stakeholders as photonics evolves and new paradigms appear on the horizon, whether they be in technology, business models, or the value chain.

An effective venture capital culture, similar to that in US that allows a rapid ramp up of innovations towards the market, should be established for European photonics SMEs, who provide the engine for industrial growth in our high-tech society, and who need access to capital in order to capture the economic value of innovations. In this respect, the provision of funds for facilitating access to capital for photonic start-ups could leverage private-sector investments. Stronger stimulation of photonic product development, pilot production, system engineering and product commercialisation is required. Europe has to support SMEs in gaining access to established and emerging markets worldwide, such as USA, China, Russia, India and Brazil. An entrepreneurship for photonic innovations has to be established in Europe at all levels. The challenge for Europe is both to lead in technology, and also to exploit related results through a successful transfer to market. As well as this, these companies still need to access the oxygen for growth necessary for securing their local market and consolidating with other European companies.

Effective standardisation processes for shortening time to market. Research projects provide relevant solutions for their targeted application fields. However, the translation from research to market commercialisation can be a slow and difficult path, which often fails to complete unfortunately. Standardisation is a key for the industrialisation of research solutions, but frequently takes too much time and money, hindering research solutions in reaching a global market. Therefore standardisation processes need to be addressed to achieve simplification and so improve effectiveness.

Fostering synergies along the entire value chain is pivotal for aligning the efforts of all the players involved. As the network evolves to an

The tight coupling of ICT technologies in end-user solutions illustrates clearly the leveraging effect that photonics communication technologies bring to Europe.

Emerging paradigms, such as 'software-defined photonics', underpin the need for consolidation of networks and systems with the underlying photonic components.

increasingly dynamic and flexible eco-system, there is a growing need for smarter and more reconfigurable photonic components. Emerging paradigms, such as 'software-defined photonics', underpin the need for consolidation of networks and systems with the underlying photonic components. Introducing functionality along this trend tends to increase component complexity, which in turn exacerbates the cost of design, fabrication and testing necessary for the development of a new product or technology. To circumvent this challenge, it is necessary to capitalise and invest on existing platforms, such as EUROPRACTICE and FIRE, and to expand other mature and value-adding initiatives, such as ePIXfab, ACTMOST and EUROFOS, into new platforms. The goal here is two-fold: (i) to offer specialised facilities and expertise over the whole range of the value chain, namely from photonic system design and prototyping through to testing, so as to translate R&D results into innovative products, and (ii) to connect the value chain of photonics with other value chains within the ICT ecosystems, such as embedded systems, complementary telecommunication technologies, networks of the future, future Internet, and flagships.

To boost Europe's competitive advantages, elements of the value creation chain, ranging from research through the building of products, have to be synchronised. In this context, it is proposed that already existing organisations, networks and platforms are embedded into a new streamlined value creation chain through the creation of the following specific European platforms, each characterised by a set of well-defined functions and interfaces:

EuroLab – European Photonics Laboratory: The EuroLab is a federation of academia, research institutes and industry that pool their joint expertise. To cover the whole value chain, there will be be networking, systems, and component/subsystems groups. Industrial partners can pose questions and raise study items that are then subsequently investigated by smaller teams. Topics will include forward-looking product ideas, technical feasibility studies, open questions in standards, and research requests to continue feeding the innovation cycle 5 to 10 years ahead. The evaluations will be theoretical, simulations, lab experiments or a mixture. The process for this must be lightweight and must guarantee commercial confidentiality, although it is expected that the majority of results will subsequently be made available publicly, and will also form the basis of on-going technology roadmapping. This can be seen as an evolution of a Network of Excellence, where there is funding for the academic partners to address the study items set by industry partners.

EuroSaP – European Photonics Specification and Prototyping: To date, EC projects have comprised largely of precompetitive research carried out by independent parties. While this has helped to build up knowledge (and some IP), commercialisation of the results has been limited, and the results are largely uncoordinated or at best complementary. A mind-set change is required with respect to the focus of these activities: more people from the product side need to be involved, to ensure the necessary upfront agreement on joint product solutions. An industry consortium-driven approach will be necessary to agree such a common framework for future product solutions and to define the specification of the constituting components. Partners across the whole value chain will be involved, from network operators, to system, optical subsystem, component and ASIC vendors. The individual consortium composition will of course be dependent on the specific project. Differentiation is possible by customisation of the components and/or the way in which such solutions would be used in a network/system context. An example of a successful agreement on a worldwide scale is the 100G long-haul multi-source agreement group in the OIF, which has demonstrated the effectiveness of such an approach. EuroSap will work independently or liaise with other groups (e.g.

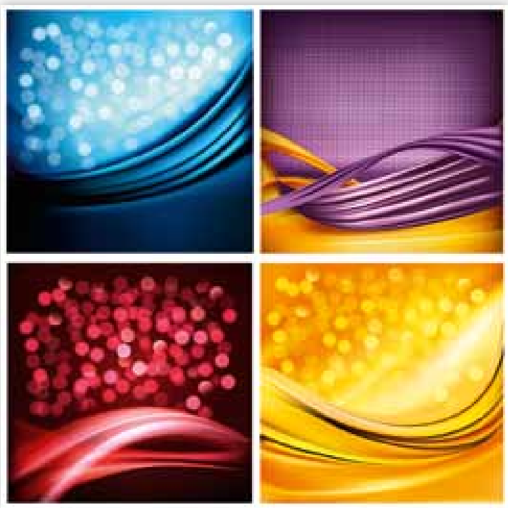
ETSI) in defining such multi-source agreements outside the EU, and, in addition to the specifications, would also be responsible for the implementation with European partners. A successful example of such an implementation is the 100G consortium in Japan, where, under leadership of NTT, all major system and component vendors have jointly developed the necessary components (based on the OIF specification) required for the realisation of 100G coherent interfaces, with substantial funding from the Japanese government. Continuing these collaborative activities, the same consortium is now already working on solutions for 400G. Based on Europe's strength in the design & manufacturing of photonics and electronics, it is desirable to also adopt a similar approach in Europe, for example in the following breakthrough technologies:

- **Access:** Low-cost tunable SFP+ DWDM transceivers for TWDM-PON and P2P applications
- **Access:** Ultra-compact N×10G DWDM Tx/Rx arrays for TWDM-PON and P2P applications
- **Backbone:** Ultra-compact Tx/Rx components for 2nd generation 100G coherent transceivers (based on Silicon or InP, integrated RF electronics, common form factor)
- **Backbone:** 1-Tbps software-defined transceivers (array transmitters and receivers with integrated RF electronics at 2–3 times today's baud rate, Tbps DSP, Tbps OTN framer)
- **Interconnects:** Tbps active optical cable

The developments will be carried out by value chain partners within the consortium, and will make use of EuroFab facilities where indicated. System vendors will then leverage these developments to build system and network solutions, and then test them with carrier partners.

EuroFab – European Photonics Fabrication: This activity deals with photonics fabrication in Europe, and aims at leveraging and extending activities already started in projects such as EuroPIC (covered by Work Group 6 *Optical Components and Systems*). European research on photonic chips has resulted in many innovative ideas. However, the connection between the chip itself and a component or subsystem that can be used in an optical communication system, often needs strengthening. The packaging of the components, the integration with the necessary RF and control electronics, and the overall integration into a module and subsystem are all critical points for successfully turning a photonic chip design into a commercial product. Specifically for new components, custom drivers and/or control electronics are often not available and may need to be designed, manufactured, and integrated. Assembly technology, and electrical, mechanical and thermal management are critical components that need to be considered in the design flow, and for defining tooling support and partner set. EuroFab will be a network of partners that develops and follows a common design flow, and which can be used for developing large volume, standard products, as well as application specific solutions. Given the fact that some of the disciplines here require very specific knowledge, there is a large opportunity in this area for SMEs, who could offer their services in addressing one or several steps throughout the entire process. Based on the current European fab capabilities, components and subsystems based on silicon, InP and polymer photonics will be the likely focus of this activity.

Optical fibre communication enhances the knowledge society.



Photonics drives the future internet. © Fotolia

EuroTaP – European Photonics Trial and Procurement: This activity aims to foster the early adoption and ramp-up of new innovative technology by creating testbeds for verifying the technologies and experimenting with value added application that can then be delivered over such infrastructures:

Traffic volume in the core network is expected to grow by a factor of 10 over the next 5 years.

- Using public procurement in European research and education networks in order to deploy innovative core network technologies (specifically software-defined optics and software-defined networking control paradigms), and gather first-hand feedback. In the procurement processes of national research and education networks (NRENs), priority will be given to products/vendors with design and manufacturing in Europe. Innovation is anticipated at both the hardware and software levels. Consequently, such testbeds are very suitable for testing capabilities of new software running on innovative new hardware, as well as for bringing early prototype hardware into the field (for example, out of EuroFab and EuroSaP).
- Incentivising fibre build-out in wireless and wired aggregation networks, and combining funding for fibre infrastructure measures with the directive to purchase network equipment, wherever possible, from European manufacturers. Leveraging such network infrastructure to demonstrate new applications and services, and providing a testbed for players to demonstrate IT/Cloud and networking convergence.
- A similar set-up will also be considered for universities to create a testbed for datacentre interconnect and switching technologies; again, a clear preference should be given to products developed/manufactured in Europe.

The proposed timeline for EuroLab, EuroSaP, EuroTaP and EuroFab, as applied to the previoulsy listed backbone technology examples, is illustrated in the following table.

Major photonics research & innovation challenges

With respect to photonic networks, the following research and innovation challenges exist:

Broadband terrestrial backbones. The exponentially growing data consumption in fixed and mobile access puts more and more stress on the core of the network. In fact, based on various traffic measurements and predictions, traffic volume in the core network is expected to grow by roughly a factor of 10 within the next 5 years, and by a factor of 100 within the next 10 years. Peak throughput at core network nodes is expected to reach several 100 Tbps by 2020. Technologies utilised in optical networking are approaching fundamental limits set by physics and information theory, and will therefore require extraordinary research effort to extend further. Several options exist for coping with future capacity demands of the optical core network, for example, increasing baud-rate, constellation size, additional wavelength-bands, flexible grids, or by utilising spatial or mode multiplexing. Electronic functionalities (e.g. A/D converters, regenerators) should be implemented on a photonic basis (e.g. photonic A/D, all-optical regeneration), offering potential cost reductions, increased data rates, and reduced energy consumption. All these options require significant advances in technology, and

Product line	Pre-*Horizon 2020*	2014/2015	2016/2017	2018/2019
Backbone: **Tx/Rx for next generation 100G**	Applied research from EU FP7 and national projects, e.g., IDEALIST, GALACTICO, ASTRON	**EuroSaP:** specifications and prototyping **EuroFab:** production of early components **EuroLab:** evaluation of developed components and modules	**EuroTaP:** deployment in EU NRENs, transfer to volume production (EuroFab)	**EuroFab:** volume production
Backbone: **Components for Tbps software-defined transceivers**	Applied research from EU FP7 and national projects, e.g., IDEALIST, SaSER	**EuroLab:** research and agreement on common strategy and components	**EuroSaP:** specifications and prototyping, **EuroFab:** production of early components **EuroLab:** evaluation of developed components and modules	**EuroTaP:** deployment in EU NRENs transfer to volume production

would probably have to be used together to enable the core network to cope with the predicted traffic demand from the network edge. To achieve transmission rates approaching 1 Tbps per channel, substantial research effort will be required at the component level (efficient, linear and broadband E/O and O/E converters, new fibre types, new optical amplifiers, optical regenerators), on electronics (analogue-to-digital and digital-to-analogue converters, linear amplifiers, power-efficient signal processors), and on processing (signal processing algorithms, advanced coding techniques). Rapid prototyping and test of PICs and their subsystem will be key factors for success.

Optical network and IT convergence. Optical networking is essential for interconnecting datacentres and enabling users to access their content and applications. It may also play an increasing role inside datacentres. Cloud based datacentres have recently absorbed many PC-type applications, such as email, productivity tools, and customer relationship management. These applications are generally considered as requiring low user interactivity. Highly interactive, multi-media PC applications, such as video editing, computer aided design, and games consoles, are also increasingly being moved into the cloud. When computing and data storage is handled largely in remote datacentres, networking becomes the performance bottleneck. The solution to this problem requires a close orchestration of IT and networking resources under a common umbrella. It includes the development of new switching architectures, advanced QoS mechanisms, and dynamic connection or flow management following a software-defined control paradigm. Optical transport and switching technologies need to integrate seamlessly into such an ITC orchestration framework. The higher degree of automation and coordination will lower provisioning time and costs for service providers, and will allow them to benefit from new value added commercial services and revenue streams.

Next-generation optical access networks will provide multiple services simultaneously over common network architectures to different types of customers.

Broadband fibre based access: Next-generation optical access networks are foreseen for providing multiple services simultaneously over common network architectures to different types of customers. Access networks capable of interconnecting higher number of users with a symmetrical bandwidth of up to 10 Gbps per customer are required. The aim is to achieve the requested capacity, QoS performance, and latency constraints in the access network, by exploiting the vast available bandwidth. The challenge will be in exploiting the full fibre bandwidth to create a hierarchically-flat access network. Additionally, there is a technical challenge concerned with the possibility of ultra-long-reach access performance, that is, 'unregenerated' transportation of the multiple data channels over long distances. Future long-reach access networks will consolidate the metro-access network structure, especially by reducing the number of required central offices that subscribers are connected to. The development of truly cost-effective integrated components and sub-systems with low power consumption is required for the high-speed optical access network. This must support the specific requirements, such as low latency, for extended wireless features like Collaborative Multi-Point (COMP) operation, and self-optimisation and topology control have to be addressed. Furthermore, optical access networks will play an important role when so-called cloud based radio access network (C-RAN) architectures are rolled out. Increasing demand for spectral efficiency and operation of mobile wireless access in more and more bands requires an increasingly higher number of deployed wireless access nodes, capable of supporting multiband wireless access and increasingly more cooperative features. For the sake of flexibility and more future-proof deployment of fibre infrastructure, it is expected that next generation fibre access networks for mobile front- and back-haul must support heterogeneous transport of digital (and digitised) signals to and from wireless access points, including aggregation and routing, thereby starting a new era of mutualisation and convergence of fixed and mobile networks.

Optical interconnects lighting the datacentre: New broadband applications are transforming the Internet into a content-centric network, fuelling the proliferation of datacentres. The new trend of warehouse-scale datacentre computing is raising the bar for high-speed interconnection, requiring unprecedented information densities and link counts, whilst simultaneously causing the energy requirements of a typical server farm to surge. The use of parallel optics for rack-to-rack communication has proven decisive for current systems, but is not enough for sustaining performance enhancements and containing energy consumption. Low-energy photonic solutions have to penetrate at all levels of the interconnect hierarchy, from rack-to-rack and board-to-board, to chip-to-chip and intra-chip data links, in order to accommodate the traffic and avoid an explosion in energy consumption. Following current proof-of-principle demonstrations, the focus will be towards low-cost technologies capable of overcoming the cost barrier for massive adoption. Addressing diverse application scenarios, with transmission distances ranging from a few mm in the case of on-chip interconnects and reaching up to 2 km for campus networks, presents a very broad set of challenges, and necessitates the development of tailored technology solutions for each application. In this context, performance enhancement would be achieved in each case through an appropriate mix of disciplines, such as the upgrade of channel rate or the introduction of additional degrees of parallelisation (wavelength- and space-multiplexing or multi-level modulation). Effective integration of optics at all levels of interconnects demands a holistic design approach for the entire system (processor, server, datacentre), so as to ensure optimal use of system resources and maximise power efficiency.

In general, innovation will be required:
To make optical networks more transparent and secure. By removing unnecessary optical-electrical-optical conversions in aggregation nodes, routers and switches, whilst managing the resulting increase in heterogeneity in fibre types and network architectures. By allowing several bit-rates, modulation formats, and radio standards to travel across the same generic infrastructure, enabling future-proof and cost-effective convergence of mobile and fixed, metro and access networks. By providing optical layer security to enable secure exchange of data in the network on the lowest possible layer.

To make optical networks more dynamic and cognitive. By introducing true flexibility in photonic networks through fast-established circuits or optical packets, coping with varying traffic demands, benefiting from flexibility and elasticity in format, channel spacing or bit-rate. This while reducing latency, and managing quality of service at the photonic layer, so achieving autonomous operation of photonic network elements, including self-diagnosis, restoration and optimisation with efficient use of monitoring and adaptation capabilities.

To make optical networks faster. By deploying a disruptive mix of technologies to match the predicted capacity growth of a typical 1 Gbps per user in wireless access by 2020, to a typical 10 Gbps per user in wired access and to a typical 1 Tbps per channel in the core. This involves coherent detection with intelligent digital signal processing, exploiting all modulation spaces and multiplexing schemes, thereby increasing spectral efficiency, whilst expanding the bandwidth of optical amplifiers and improving their noise properties.

To make optical networks greener. By expanding the role of photonics from core down to home access, and promoting optical bypassing whenever possible. By turning all photonic equipment to idle mode when possible, and performing power-efficient all-optical switching and processing as appropriate. By simplifying or removing unnecessary protocols, and performing energy-aware optical routing to reduce cost per transmitted and routed bit.

To bring optical networks closer to the customer. By ensuring high-bandwidth, mobile, fast, green, secure, and reliable customer services by optical wired and wireless home and in-building networks.

Expected impact for Europe
In most countries information and communication technology infrastructure is now considered to be a critical part of its national infrastructure and the key to future economic growth. The ICT sector is directly responsible for 5% of Europe's gross domestic product, with an annual market value of €660 billion. As an enabler, ICT plays a vital role in enhancing other sectors' business growth. According to the Photonics21 study *The Leverage Effect of Photonics Technologies: the European Perspective*, photonic technologies leverage a telecommunication infrastructure market of €350 billion and impact more than 700,000 jobs in Europe (2010).

Photonic technologies leverage a telecommunication infrastructure market of €350 billion and impact more than 700,000 jobs in Europe.

Broadband has the power to spur economic growth by creating efficiency for society, businesses and consumers. Both broadband availability and transmission speed are strong drivers in an economy.

Doubling the broadband speed for an economy increases GDP by 0.3%, which is equivalent to $126 billion in the OECD region. This growth stems from a combination of direct, indirect and induced effects. Direct and indirect effects provide a short to medium term stimulus to the economy. The induced effect, which includes the creation of new services and businesses, is the most sustainable dimension, and could represent as much as one third of the mentioned GDP growth. If broadband

Roadmap for 2014 – 2020

	Pre-*Horizon 2020*	2014/2015
Broadband terrestrial backbones and datacentre hosted cloud applications	Applied research on broadband terrestrial backbone systems to increase overall system and network performance, funded in national and EU projects, e.g.: **SaSER** focusing on save and secure routing. **IDEALIST** focusing on transport systems enabling flexible transmission and switching of 400 Gbps and beyond per channel. **ASTRON** focusing on adaptive software defined terabit transceivers. **GALACTICO** focusing on TbE integrated coherent transmitters and receivers.	Development of further concepts to increase overall network performance with respect to capacity, speed, power consumption, security and flexibility with the focus on: ■ Concepts for a next generation of 100/400 Gbps transponders with lower power consumption, smaller form factor, and lower cost ■ Concepts for system architectures to deliver up to 1 Tbps per channel and up to 1 Pbps per fibre in the core/metro network ■ Concepts for contention-less ROADMs capable to handle Tbps-signals in a flexi-grid environment ■ New concepts for elastic bandwidth allocation, switching and resource defragmentation; concepts for virtualisation of network resources ■ Software-defined network control, approaches towards cognitive and self-managed optical networks, solutions for network programmability on application level Value creation through extended field tests with completed 400 Gbps systems in National Research and Education Networks (NREN). Ramp-up of system and device production.

speed is increased, short-term jobs will be created to build the new infrastructure. As an induced effect over a 5 years period, new ways of doing business are established, more advanced online services and new utility services are initiated. Indirect effects, such as spillovers to other industrial sectors, are initiated on a longer time scale, 10 to 20 years, and result in an efficiency improvement of the economy. Connectivity and broadband are just a starting point for new ways of innovating, collaborating and socialising.

2016/2017	2018/2019	2020
Development of highly integrated sub-system solutions for Tbps signal generation, transmission, routing, detection, and processing: ■ Tbps SDO components based on Silicon/InP ■ Enhanced digital signal processing units, FEC solutions, coded modulation ■ High-speed optical-to-electrical and electrical-to-optical interfaces with low power consumption at low cost jointly integrated with high-speed pre- and post-processing DSP units ■ Software-defined transceivers ■ Low noise optical amplifiers and regenerators ■ Robust excitation units for few-mode- and multicore fibres ■ Contention-less flex-grid ROADMs Dedicated prototyping of devices and sub-systems. Building up common test equipment and platforms for tests at device and (sub-) system level.	System design, integration and verification for selected high-impact applications: ■ Demonstration of flexible Pbps core/metro networks using elastic bandwidth allocation and resource virtualisation ■ Demonstration of OpenFlow controlled networking for datacentre hosted cloud applications connected to Pbps optical transport systems Building up user groups and competence networks to demonstrate, evaluate and promote the selected high-impact applications.	Deployment in European NRENs. Transfer to volume production.

	Pre-*Horizon 2020*	2014/2015
Broadband terrestrial backbones and datacentre hosted cloud applications		■ Novel concepts for an integration of optical switched network architectures and cloud server technologies and their associated control and data planes into a singular architectural object Proof of concepts in lab experiments to derive required device and system specifications.
Broadband fibre based access and in-building networks	Applied research with the focus on broadband fibre based access and in-building networks, funded in national and EU projects, e.g.: **OCEAN** focusing on >20 Gbps OOFDM based access. **OTONES** focusing on OFDM-PON with colourless transceivers. **CRITICAL** focusing on 1 Gbps+ coherent access systems with DSP. **TUCAN** focusing on low cost tunable transceiver technology. **OPTAIN** focusing on LTE backhauling. **FIT** focusing on the gateway functionality to central office and home area networks. **C3PO** focusing on colourless and energy efficient optical components for future access.	System demonstrations of on-going research initiatives serving as a catalyst to new concepts to increase overall network performance with respect to capacity, speed, power consumption, security and flexibility to deliver 10 Gbps+ to the user in metro/access and 1 Gbps+ in in-building networks with the focus on: ■ Convergence of wire-line and wireless access network technologies ■ Convergence of access/metro/core network technologies ■ Networking-assisted virtualisation and pooling of IT appliances for security, bandwidth and content ■ Cloud based access services ■ Dynamic optimisation of Quality of Experience by orchestration of networking and content delivery Value creation through extended field tests with completed systems in smart city environments.

	2016/2017	2018/2019	2020
	Value creation through early field tests.		
	Development of highly integrated sub-system solutions for next generation optical access architectures focusing on: ■ Low-cost SFP+ tunable transceivers ■ N×10G Tx/Rx DWDM arrays at low cost ■ High-speed optical-to-electrical and electrical-to-optical interfaces with low power consumption at low cost jointly integrated with high-speed equalisation (e.g. DSP, equaliser) units ■ Silicon/InP hybrid integrated circuits; 3D integrated devices; Introduction of polymer materials towards cost effectiveness and low power consumption ■ Visible light communication and navigation, integrated solutions for lighting and communication Dedicated prototyping of devices and sub-systems.	System design, integration and verification for selected high-impact applications: ■ Demonstration of flexible Pbps core/metro networks using elastic bandwidth allocation and resource virtualisation ■ Demonstration of OpenFlow controlled networking for datacentre hosted cloud applications connected to Pbps optical transport systems Building up user groups and competence networks to demonstrate, evaluate and promote the selected high-impact applications.	Deployment in European NRENs. Transfer to volume production.

	Pre-*Horizon 2020*	2014/2015	
Broadband fibre based access and in-building networks		Proof of concepts in lab experiments to derive required device and system specifications. Ramp-up of system and device production at low cost for 1 Gbps+ per subscriber.	
Optical interconnects lighting the datacentre	Applied research on optical interconnects to increase device and system performance, funded in national and EU projects, e.g.: **SEPIANet** focusing on optical coupling techniques for chip to PCB, optical board-to-board interconnects and pluggable optical PCB connectors. **PLATON** focusing on the demonstration of a Tbps silicon-plasmonic router for optical interconnects. **MIRAGE** focusing on Terabit board-to-board and rack-to-rack parallel optics. **PHOXTROT** focusing on photonics for high-performance, low-cost and low-energy data centres and high performance computing systems. **POLYSYS** focusing on a disruptive capacity upgrade in data centres using a polymer integration technology. **PLAT4M** that focuses to bring existing silicon photonics research platforms to a maturity level which enables seamless transition to industry.	Penetration of the optical technology to the whole datacentre/HPC eco-system and in all interconnection layers: ■ Optical networks on chip ■ Optical on-board interconnections ■ Optical backplanes ■ Active optical cables exploiting advanced modulation formats ■ Data transfer architectures to accommodate datacentre topologies and server inter-connections ■ Exa-FLOP high-performance computing and Zetta-byte storage Proof of concepts in lab experiments to derive required device and system specifications. Value creation through launching of products and transfer to volume production.	

	2016/2017	2018/2019	2020
	Building up common test equipment and platforms for tests at device and (sub-) system level. Value creation through early field tests.		
	Development of integrated solutions for optical inter-connection concepts with the focus on: ■ Multi-layer optical PCBs ■ Single-mode PCB solutions for on-board and board-to-board interconnections ■ New interfacing approaches to facilitate the inter-connection of various interconnection layers ■ Exploitation of Silicon and Polymer integration tech-nologies to achieve low cost and low power consumption ■ 3D-integrated devices ■ Active optical cables Dedicated prototyping of devices and sub-systems. Building up common test equipment and platforms for tests at device and (sub-) system level. Value creation through early field tests.	System design, integration and verification the demonstration of an optically inter-connected datacentre including: ■ Networks on a chip ■ On-board interconnects ■ Optical backplanes ■ Active optical cables Building up user groups and competence networks to demonstrate, evaluate and promote the selected high-impact applications.	Deployment in European NRENs. Transfer to volume production.

	2014 – 2020
Innovation requirements	Strengthen the interworking between industry and research institutes by creating platforms (EuroLab, EuroSaP, EuroFab, EuroTaP) to launch innovative products; strengthen the involvement of existing producers of photonic components, (sub-) systems and network elements. Ensure that IP and innovation stays in Europe. Ensure that photonics telecommunication industry and manufacturing is strengthened in Europe. Identifying regions for strategic long-term alliances outside Europe.
Cross-cutting Key Enabling Technologies (KET) issues	Involvement of KETs relevant for system fabrication and network installation: advanced integration, packaging, prototyping and manufacturing. Synergies exist with nanotechnologies, advanced materials, advanced manufacturing and processing, as well as to bio-technology and space.

New mass markets will be created. For example, in health care alone it is expected that 500 million people will use mobile applications. With speed requirements steadily increasing, photonic communication is mandatory for delivering broadband services to end users, either directly as optical fibre access, or indirectly as optical feeder technology to copper or radio access networks. Photonic communication technology is the key enabler for a future-proof way of living, allowing home working and learning, e-health and e-government, and other e-services.

Optical ICT technologies will play a major role in the reduction of worldwide energy requirements.

The steadily rising cost of energy and the need to reduce global greenhouse gas emissions have resulted in energy becoming one of the primary technological challenges of our time. ICT in general, and optical technologies in particular, are expected to play a major role in the reduction of the worldwide energy requirements. Indeed, recent studies show that ICT is today responsible for about 4% of the world energy consumption, a percentage expected to double over the next decade. Optical networking plays a key role in the support of energy efficient and hence sustainable future ICT solutions. The achievable level of energy efficiency will be very much dependent on the specific architectural approaches that are adopted, on the technology choices that are made, and on the use of suitable planning/routing algorithms and service provisioning schemes. In this context, it is also important to design and operate optical networks taking full consideration of the details of the services and applications that they will support, as well as the end devices they will interconnect. Attempts to match the characteristics of currently popular applications, such as P2P, grid or cloud services, to the underlying optical-based network infrastructure can further enhance energy savings for operators, service providers and users.

2.2 Industrial Manufacturing & Quality

Main socio-economic challenges addressed

Photonics is already a strategic capability for European industry and a key enabling technology for manufacturing processes, and will become even more so in future. With the 'laser light' tool, manufacturing processes can be handled automatically and flexibly, producing components and products of extraordinary quality, and in a much 'greener' way in comparison to most other energy sources.

The trend towards customisation and the growing importance of industrial design, as observed most notably in consumer electronics, will require novel methods for proving new product properties and shapes, and bespoke production capabilities. The inherent flexibility of the laser tool makes it the ideal choice for meeting these requirements. Further advantages of the laser as a working tool are that it does not wear out, it allows the integration of monitoring and control systems based on intelligent photonic sensing techniques, and it allows zero-fault production, even in single part production.

The extreme precision with which laser energy can be applied results in a substantial reduction in the total energy consumption, when compared to standard production processes. This makes laser processing an increasingly relevant technology for a future sustainable economy in Europe. The ability of the laser to machine materials that are otherwise very difficult to process with conventional tools makes it an ideal tool for fabricating lightweight, high-strength constructions, such as crash-safe car bodies or wind turbine blades. Furthermore, the laser itself will play a major role in facilitating green manufacturing, since laser processes allow for very precise, well-controlled and therefore highly efficient energy deposition on the work piece. A further environmental attraction of laser-based processes is the reduced consumption of chemicals, for example, by replacing the chemical etching baths currently used for the manufacturing of rotogravure cylinders by a laser engraving process. Innovative laser processes will increase the efficiency of photovoltaic devices and will enable energy storage devices with higher capacities; a key requirement for future electric cars.

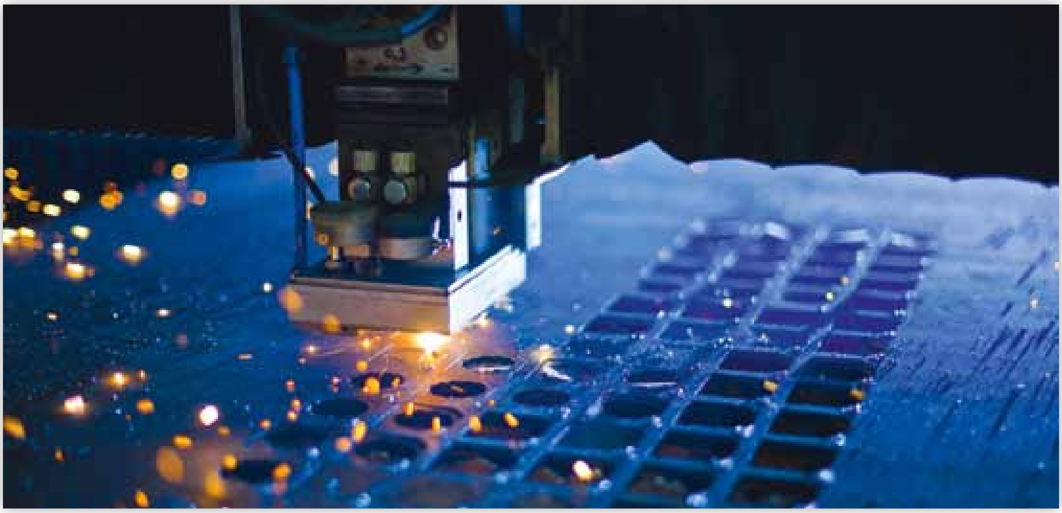
Laser deposition of metal.
© TRUMPF

Laser processing is also expected to make a significant contribution in tackling the societal challenge presented by the ageing population in Europe. This will result from the wide range of innovative new products enabled by new photonic manufacturing technologies, including such varied products as pace-makers, synthetic bones, endoscopes, and micro-cameras used for in-vivo health care processes.

Today, photonics is not solely a driver for innovation in manufacturing; the photonic technologies, laser tools and process systems themselves are a worldwide multi billion industry, dominated by European companies. Consequently, in addition to photonics aligning well with sustainable development, green technologies and resource-efficient production, it also contributes significantly to employment.

With the 'laser light' tool, manufacturing processes can be handled automatically and flexibly.

Photonic technologies, laser tools and process systems themselves are a worldwide multi billion industry dominated by European companies.



Photonics technologies are widely used in production processes. © Fotolia

The world market for laser systems in 2011 was approximately €7b with Europe taking a third of this. In specific sectors, such as in Lithographic Production Technologies, this share is higher than 50%. However, overall the European market share of this sector has declined from its 2008 value of 39%, as a result of growing competition from East Asia. Investment in developing new technologies will be essential to reverse this decline.

Laser manufacturing processes provide significant competitive advantage to the European car industry.

In addition to the direct market for laser systems themselves, use of laser processes provides significant competitive advantage to manufacturing industries, such as the European car industry, thereby greatly leveraging the economic benefits.

Major photonics needs

The major photonics need is to broaden the spectrum of applications of laser production technologies, especially so in light of the increasing demand for energy and resource efficient products. This applies to all sectors where laser technology can offer new production solutions, new product qualities, and cost benefits. Key opportunities for this include energy conversion, electronics, hybrid materials, lightweight construction, mass customisation and rapid manufacturing, print technology, and product marking.

Involvement of value chain partners

Photonics is a cross-sector technology, and Europe-wide cooperation along the entire value chain will be essential for future progress and success. All the relevant players need to be involved in R&D projects, research networks and clusters, providing the scientific and innovative solutions to manufacturing problems.

The physical and technical limitations of today's optical components can only be overcome through interdisciplinary research efforts in manufacturing technologies, microsystem engineering, nanotechnology, telecommunications, and optics. More fundamental limitations must be tackled by basic research on the interaction between light and matter, on novel materials, and on new structures with revolutionary photonic properties. This will require work in materials science, quantum optics, thermodynamics and solid-state physics.

New opportunities for design and manufacturing will require highly qualified personnel at all levels. Demand for skilled staff will continue to increase, and special efforts in education and training will be necessary to meet this demand. The creativity of skilled individuals will be a key factor in ensuring innovation and maintaining Europe's leading position in photonics manufacturing.

Major photonics research and innovation challenges

Europe has a world-leading position in the market of photonics for industrial production, with the world's largest laser companies and manufacturers of key laser components located in this region. Europe's laser technology leads in terms of innovation and optical excellence when compared to other regions. To ensure that this competitive edge is maintained, the principal research and engineering efforts have to focus on more efficient lasers (more light output for a given energy input), longer-lasting components that can be recycled, and maintenance-free manufacturing equipment. The markets for new processing strategies and new photon transmission systems must also be addressed. The most challenging problem in laser source manufacturing is price pressure, a result of the increasing cost competition exerted mainly by Asian manufacturers.

The primary research areas to be addressed will need to cover all stages of the manufacturing process, from basic research and development through to the products themselves and their market penetration.

The goal is to extend laser processing capabilities significantly beyond their current position, and thus allow many new and challenging processing applications to be addressed. For example:

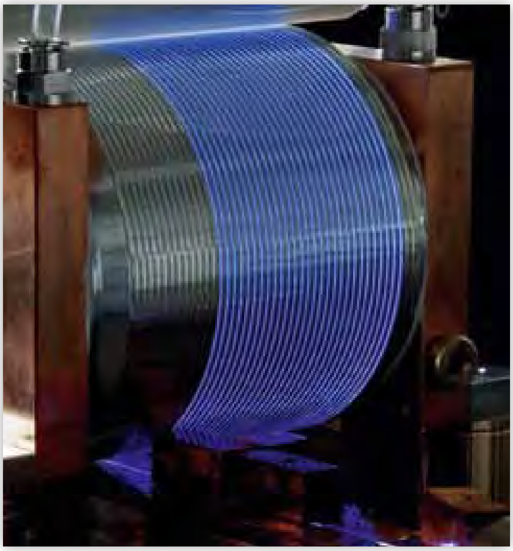
- processing of composites and dissimilar materials
- basic research on material processing and applications (e.g. composites)
- additive manufacturing (e.g. 'product printing machines' based on the selective laser melting [SLM] process)
- mass production of individual items
- colour marking
- fabrication and laser treatment of functional surfaces and advanced materials (biocompatible functional implants, nanoparticles, fibres for microelectronics, photovoltaics, flat-panel displays, laser cleaning, surface hardening, and bonding of transparent materials)

To achieve this goal, advances are necessary in both the underlying laser technology itself and the processes though which they are deployed. In terms of these laser sources and optical components, the focus has to be set on reliable, reproducible and precise methods for automated assembly of photonic devices and lasers, with improved performance in terms of power, beam properties, efficiency and size, as well as better spatial & temporal control and stability - and all at lower cost. A further key requirement will be the incorporation of adaptive reconfigurable beam delivery networks, capable of high power and intensity. New applications are expected, for example through the use of ultrashort laser pulses. However, to take full advantage of such new laser sources, new high-speed beam deflection technology also needs to be developed in parallel. These improvements will be crucial for extending laser technology to large market sectors, such as electronic industries or mass customisation of consumer goods.

Europe's laser technology leads the world in terms of innovation and optical excellence.

Principal research and engineering efforts must focus on more efficient lasers, longer-lasting recyclable components, and maintenance-free manufacturing equipment.

Lasers enhance manufacturing processes. © Fotolia



Left: 3D laser cutting. © TRUMPF

Right: Thin-disk, laser-pumped, high-brightness fibre laser developed at the IFSW for material processing applications. © IFSW, University of Stuttgart

Therefore, more efficient lasers and new photonic components will be needed, including:

- high brilliance diode lasers (output power >20W per emitter) with improved energy efficiency and beam quality
- ultra high power (>1kW), ultra short pulse (fs-ps), visible and near IR lasers
- highly efficient and long term stable UV/EUV lasers (solid state)
- cw UV direct imaging (with 100W)
- 'fully tunable' laser (pulse width tailored to the application and variable in wavelength – UV to visible to MIR)
- efficient mid-infrared laser with output power up to 1kW (e.g. 1.5–1.9 µm / 2.6–4 µm for organic materials/polymers)
- industrial MIR systems
- coatings and components (e.g. gratings, isolators) for high power/high intensity beams
- non-linear transparent materials (crystals, ceramics) for high power/high intensities (and short/UV wavelengths)
- fast modulation capability provided in conjunction with high speed scanning devices (for synchronisation)

In the drive for higher product quality, further development and production implementation will be needed for beam delivery and control, process monitoring, adaptive control of the laser manufacturing process, and quality inspection of laser manufactured goods. Aspects of integrating laser sources within machine tools, in particular robotic manufacturing tools, will also require optimisation and standardisation. This will require that the following technological challenges be addressed for beam delivery, shaping and deflection systems:

- remote technologies
- connectors and integrated beam switches
- monitored high power connectors
- diffraction limited fibre delivery of output power >1kW over a distance of 100m
- laser arrays, multiple fibre arrays, and fibres for transport of ultra-short/energetic pulses
- precise beam deflection with a target speed of 1km/s (at the work piece)
- dynamically reconfigurable intensity distributions for advanced thermal management of laser processes e.g. for welding or soldering
- new electro optic materials, beam delivery systems, and fast electronics and data processing
- standardised modular systems

Whilst for achieving the necessary improvements in quality control and sensors, the following challenges must be addressed:

- process monitoring sensors
- multi-spectral imaging sensors
- real-time process control for Fully Automated Installation (FAI) applications
- the combination of laser technology with online non-destructive testing
- multi-spectral imaging and focusing optics for simultaneous processing and observing (coaxial process control)

These advanced laser processing capabilities will also open the way to ground breaking new optical components and the corresponding technologies for their fabrication. Further, when combined with the results of accompanying fundamental work in laser beam/material interactions and process control, exciting new photonic processes for manufacturing will be achievable, offering more flexibility, more functionality and greater productivity. Such innovative components and processes are the key to realising this vision of strengthening and sustaining Europe's leading position on the world market for photonic technologies and mechanical engineering.

Expected impact for Europe

Lasers represent a versatile tool for handling a wide range of manufacturing tasks all along the workflow chain, from material processing through to quality control. Typically the added value generated with a machine tool or a laser system, calculated as a multiple of the cost of the tool itself. Taking due account of this factor, the laser processing industry on its own is a multi-billion Euro industry, and it also has a substantial leverage effect on many other industries, most notably in the European automotive sector.

In addition to the clear economic benefits for Europe, the impact of the next generation laser sources and photonic manufacturing processes on today's most challenging societal questions will be high. Three specific examples are:

- **Sustainable (Green) Economy:** Light weight cars, batteries and fuel cells, high-efficiency photovoltaic modules, to name but a few, all require laser technology for their production. An additional key benefit of using laser processing technology for green manufacturing is that lasers reduce energy consumption and chemical waste.

- **Ageing Society:** From pace-makers to synthetic bones, and from endoscopes to the micro-cameras used in in-vivo processes – laser technology plays a major role in addressing the needs of our ageing society.

- **Information Technology:** Laser-powered, extreme UV-light sources will provide the critical manufacturing tool essential for achieving future miniaturisation and cost reduction of microelectronics.

In terms of the competitiveness of European industries, the proposed research priorities will have a major impact on maintaining the established industrial leadership of laser and laser processing technologies in Europe. They will therefore have a direct and positive influence on the future advanced, laser-based manufacturing technology in Europe. Additionally, they will broaden the base of European manufacturing technology, thereby overcoming current disparities and ultimately sustaining economic strength.

Laser represent a versatile tool for handling a wide range of manufacturing tasks all along the work flow chain.

Roadmap for 2014 – 2020

	2014/2015	2016/2017	2018/2019	2020
Technological challenges	■ Efficient lasers and devices			
	■ Quality control			
	■ Beam delivery, shaping and deflection systems			
Research actions	**Efficient lasers and devices:**			
	■ Coatings and components for high power / high intensity beams			
	■ Non-linear transparent materials for high power / high intensities			
	■ Ultra-short pulse high power lasers with high repetition rate (NIR, VIS)			
	■ Fast modulation capability with synchronised high speed scanning devices			
	■ High brilliance diode lasers			
	■ Efficient and long term stable UV / EUV lasers (solid state)			
		■ Efficient, industrial MIR laser systems (up to 1 kW)		
		■ Flexible lasers (multi-color, UV-VIS-NIR-MIR)		
		■ UV direct imaging (cw, with 100 W)		
	Beam delivery, shaping and deflection systems:			
	■ Remote technologies			
		■ Diffraction limited fibre delivery (>1 kW, >100 m)		
		■ Connectors and integrated beam switches		
		■ Detectable, monitored high power connectors		
	■ Flexible beam shaping			
	■ Laser arrays, multiple fibre arrays			
		■ High speed scanning devices (1km / s)		
			■ Fibre transport of ultra-short pulses	
	Quality control:			
	■ Process monitoring sensors			
	■ Combination of laser technology with online non-destructive testing			
		■ Real-time process control for FAI applications		
		■ Multi-spectral imaging and focusing optics		
		■ Multispectral imaging sensors		
Innovation requirements	■ Large size precision optic			
	■ Laser / motion synchronisation at high repetition rates			
	■ Surface processing with <1 €/ m^2 (cost of ownership)			
	■ Highly individualised products in mass markets (transportation, medical, consumer)			
	■ Broad scaling range: macro – micro – nano			
Cross-cutting Key Enabling Technologies (KET) issues	■ Greener products: less chemical processing, less energy consumption			
	■ New surfaces/materials with impact on: energy, medical, electronics/semiconductor, lightning and manufacturing technologies			
	■ New products with impact on bio tech, medicine, nano tech, advanced manufacturing			

2.3 Life Science & Health

Main socio-economic challenges addressed

Progress in the field of photonic methods and techniques for Health and Life Sciences will contribute significantly to solving several of the 'grand challenges' of our time as defined in the Lund Declaration of July 2009, by offering "sustainable solutions in areas such as … water and food, ageing societies, public health, pandemics …".

For most European countries, the projected demographic changes will have drastic consequences for European citizens and their healthcare systems. For example, the number of people older than 65 years will double by 2030, leading to a dramatic growth of age-related diseases including Alzheimer's disease, cardiac infarction, stroke, age related macular degeneration, diabetes, kidney failure, osteoarthritis, and cancer. Greater mobility of the population will result in the increased occurrence of pandemics. Therefore, providing adequate health care for all European citizens will require enormous efforts. These challenges can best be met through breakthroughs in and deployment of Biophotonic technologies, yielding new cost-effective methods for improved diagnosis and therapy. These same technologies can also serve to control water and food quality, thereby reducing diseases caused by contamination.

Major photonics needs

A major step towards tackling these challenges will be to focus Biophotonics research and innovation on the development of easy-to-access, minimally invasive, low-cost screening methods. These will be based on photonics point-of-care methods and technologies, providing a risk assessment of age and life-style related diseases (ideally risks factors for a combination of several diseases would be assessed simultaneously), thus establishing a reliable result within minutes.

Detailed investigation, employing more advanced diagnostic methods to locate and precisely evaluate the origin of the disease, would then be undertaken if the screening returned a positive result for one of the disease parameters. Improved diagnostic and interventional methods will be developed, based on improved multi-band (X-ray, Ultraviolet, Visible, Near/Mid/Far IR, Terahertz) photonics, spectroscopic and endoscopic devices. These should provide more reliable and precise examinations than current 'gold standard' methods, without increasing examination costs or duration. An illustrative example is provided by the diagnosis of bowel cancer, where the established procedure (white-light colonoscopy) is neither precise nor sensitive enough to detect all cancerous lesions, and is considered too invasive a screening tool for the majority of the population. Improved screening should therefore indicate where further diagnostics was necessary, and improved diagnostics could precisely locate and analyse the disease, before therapeutic measures were initiated. These could incorporate multi-band photonics techniques to provide safer, personalised treatment methods, tailored for specific therapy and treatment monitoring.

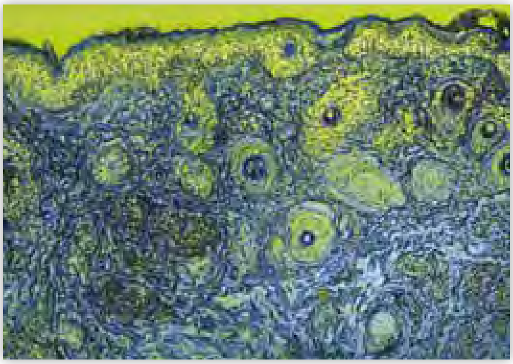
In addition to their use for the diagnosis and treatment of diseases, multi-band photonics methods could also provide preventative tools, for example, offering analytical methods to monitor and evalu-

Breakthroughs in and deployment of Biophotonic technologies will yield new cost-effective methods for improved diagnosis and therapy.

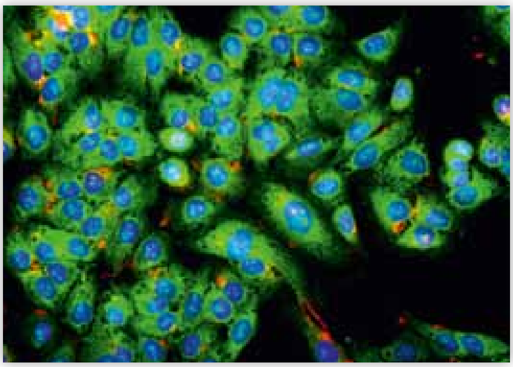
The trend towards an ageing society in Europe will increase over the decades. © Fotolia ate water and food with regard to quality and potential microbial contaminations. The methods that would be employed for this could be essentially the same as used for advanced screening, perhaps with minor adaptations for the specific target. There is considerable synergy with the sensing requirements for Work Group 5 *Security: Metrology and Sensors*, and it is therefore anticipated that there will be common solutions, making close collaboration in this field highly beneficial.

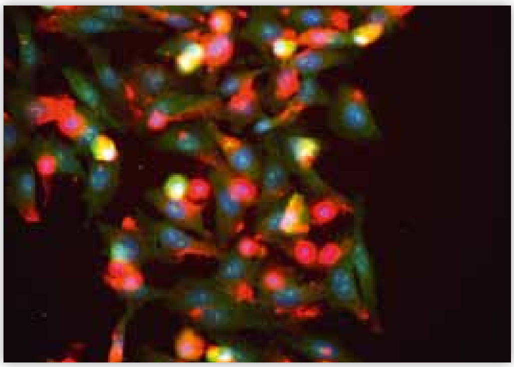
Involvement of value chain partners

Biophotonics in itself is already a highly multidisciplinary field, involving physicists, chemists, and engineers as method and technology developers, as well as end-users from the fields of biology and medicine. To some degree, industry already reflects this diversity, comprising component and system developers, as well as full solution providers. Over the last few years, component developers have shown a growing awareness of the increasing importance of Biophotonics, and this has been reflected in the growing level of revenues generated in this field. The frontiers between system developers and full solution providers often become blurred, particularly with the growing realisation that the end-users of Biophotonic technologies generally prefer purchasing everything from a single source. Since most of the Biophotonic technologies and methods are, with the exception of conventional microscopes or current X-ray machines, still relatively new, the leading medical device manufacturers have to date shown relatively little interest, and so have limited market presence in this sector. A major breakthrough for Biophotonics in the medical devices market would require a significant increase in the involvement of these companies. Similarly, the early and substantial involvement of the potential end-users, especially that of physicians and clinicians, at all stages of development will be of utmost importance. The involvement of end-users will be critical for the development of solutions tailored to fit their specific needs. Such direct involvement will greatly help maximise the integration of new tools and techniques within the established process flow employed in the clinical environment. The involvement of end-users is generally not an easy task, especially for clinicians, as their steadily increasing burden limits the time available, and their focus on patient welfare tends to result in a relatively conservative attitude to new approaches. This activity would be strengthened by extending the ongoing collaboration with the Nanomedicine European Technology Platform (ETP), though additional measures would also be

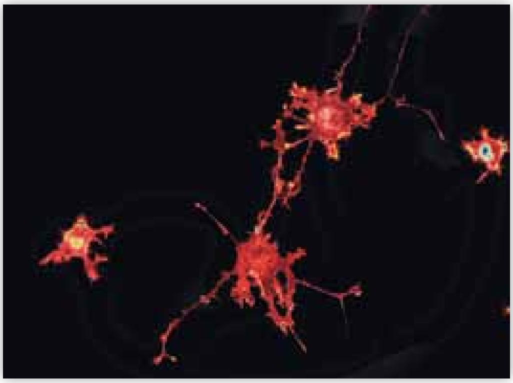


Biophotonic technologies and methods will lead to improved diagnosis and therapy. © IPHT Jena

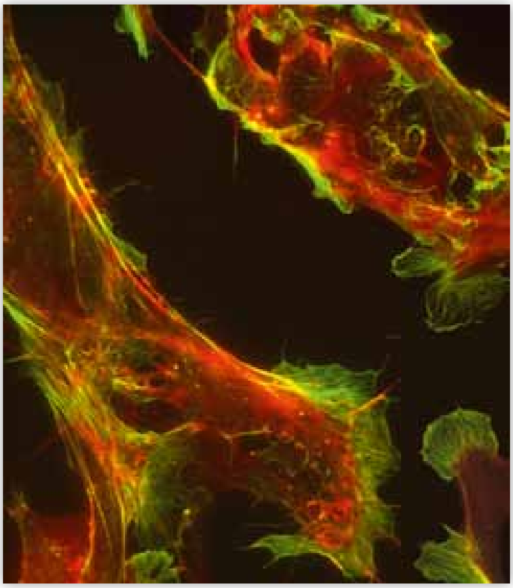




Left and Right: Photonic imaging of tissue samples. © BioImaging Zentrum (BIZ), LMU München essential for reaching out further into the medical world. Additionally, it will be vital to connect with the medical insurance companies to identify and implement opportunities for public procurement. This will lead to precise, reliable, gentle and user-friendly multi-band photonics and spectroscopic methods, widely deployed in clinics, doctors' practices, and other locations where they provide added value. For addressing food and water quality and safety, connections to the ETP Food for Life, the ETP Global Animal Health, and the ETP Water Supply and Sanitation would be greatly advantageous.



Cells that have been coloured using membrane colourant. © BioImaging Zentrum (BIZ), LMU München



A non-neuronal cell of the central nervous system whose cytoskeleton has been coloured. © BioImaging Zentrum (BIZ), LMU München

Major photonics research & innovation challenges

In preparation of the second Photonics21 strategic research agenda, Work Group 3 made an evaluation of the different application areas within Biophotonics to establish where unfulfilled but pressing needs existed, and where the employment of multi-band photonics and spectroscopic methods could really make a difference. As a result, five specific areas of health-related application fields were identified as being particularly important and promising, supplemented by further applications in the fields of the environment, food quality and security.

Preclinical research: Although many multi-band photonic and spectroscopic methods could already be deployed today for the benefit of the patient, the ultimate goal of preclinical research is to understand the origin and progress of a disease, from the organ and tissue down to a cellular or even molecular level. This knowledge would allow detecting, curing or even preventing diseases long before the onset of macroscopic symptoms. The prerequisite for gaining such a holistic understanding of life processes are tools and methods that allow seamless observation from the macro- through the micro- and down to the nano-level, without changing or disturbing these processes. The observation should be possible with high resolution and in three dimensions, as well as with sufficient time resolution to reveal fast processes. There will be correspondingly large demands made for data processing and storage. Major improvements will be needed with regard to sensitivity, specificity, contrast and penetration depths.

Oncology: Cancer belongs to the group of diseases whose incidence rates often increase with age, and it is therefore one of the fastest growing threats to people's health, especially in Europe. The 5-year survival rate drops rapidly if cancer is not detected before its later stages, therefore early detection is of paramount importance. Unfortunately, for many forms of cancer, screening is either not possible, ineffective or unpleasant (such as colonoscopy). Today's methods of detection often lack sufficient specificity or sensitivity for the consistently early and conclusive detection of cancer. Then, The eye can provide a 'diagnostic window' to the body, offering easy and minimally-invasive access to key parameters identified with cardio-vascular diseases, diabetes or Alzheimer's disease.

even when a cancer has been detected correctly, determining its physical extent for subsequent removal frequently presents a major challenge. A two-step procedure is envisaged for screening citizens for a range of different cancers. In the first step, photonic (or a combination of photonic and non-photonic modalities, such as ultrasound and magnetic resonance) point-of-care technology would be applied to provide a low cost, rapid and reliable risk assessment for a particular cancer or combination of cancers. If the result of this screening indicates risks, advanced and improved analytic (multi-band photonic/spectroscopic) methods, developed for locating and analysing the cancer in a sufficiently reliable and precise way, will be applied. It is likely that these techniques will make use of label-free methods, since the time needed for development of a tool such as an endoscope is usually much shorter than the period necessary to get safety approval of labels for in vivo applications. The techniques could, if advantageous, also employ a combination of photonic and non-photonic technologies, such as ultrasound, magnetic resonance or nuclear scanners. The same techniques or combinations thereof, employed for localising and identifying a tumor, might also be applied in an surgical microscope or in an endoscope for determining the physical extent of degenerated tissue with unprecedented precision, and thus allow the complete removal of this tissue. In cases where removal is not possible, for example, in the case of large area distributed lesions, as can occur for skin cancer, highly targeted treatments based on light, possibly in combination with other effective self-targeting therapeutic approaches, may provide the means for selectively eliminating cancerous tissue.

Infectious diseases: Often the outcome in the case of infectious diseases can be highly dependent on the time interval between onset of infection and administration of therapeutic agents. This is particularly true for sepsis, which is still one of the most underestimated but life-threatening diseases occurring in the clinical practice. Ideally, a suitable therapeutic agent should be administered within one hour after the occurrence of a septic shock. Sepsis can be caused by a wide range of bacteria, as well as by fungi and viruses, so it is of vital importance to identify the specific pathogen responsible. Conventional techniques like cultivation and even new techniques based on polymerase chain reactions (PCR) are often too slow or not sufficiently reliable. These techniques need to be replaced by methods that are really capable of making a difference. Similar techniques, as envisioned for use in screening, will also have the potential to reliably identify pathogens, determine potential antibacterial resistances, and evaluate the host's immune response. This will enable the administration of targeted agents, avoiding the use of broad-spectrum antibiotics that could facilitate antibacterial resistance. If resistant bacteria are encountered, targeted photodynamic therapies offer a potential solution, especially since their mode of action does not promote resistances. Photonic technologies can also be employed for treatment monitoring (for example, for infectious diseases or cancer therapy) to measure progress and identify necessary treatment modifications, as well as monitoring of the local environment and food to prevent the outbreak of infections (for example, food poisoning from Staphylococcus aureus, described below). Ultimately, very cheap photonic monitoring devices could even be incorporated directly into bandages, infusion sets, etc..

Ophthalmology: Although the eye itself is a tissue affected by age-related diseases, such as retinopathy or geriatric macular degeneration, it can also provide a so-called 'diagnostic window' to the body, offering easy and minimally-invasive access to the key parameters identified with cardiovascular diseases, diabetes or neurodegenerative diseases such as Alzheimer's disease. In addition to the currently available morphological information, functional information could help diagnose eye diseases earlier and in a more personalised manner.

Therefore the challenge in this field consists of developing optical and spectroscopic techniques and tools that can be applied in a (pre)clinical environment. These would be used in combination with already existing modalities focusing on morphology, such as optical coherence tomography, to investigate the functional and metabolic state of the eye.

Neuro-monitoring and imaging: Photonics based tools provide unique contrast for in vivo imaging, and access to key physiological parameters for neuro-monitoring and imaging. In particular, these technologies enable researchers and, increasingly, clinicians, to measure parameters such as cerebral hemoglobin oxygenation, hemoglobin concentration, blood volume, blood flow and oxidative metabolism. Photonics technologies are, by their nature, non- or minimally-invasive, harmless, continuous, portable, inexpensive, and are therefore very well suited to a clinical environment. They are used to monitor the human brain, from neonatal to adult populations, in various applications, ranging from the understanding and management of preterm birth related pathophysiology of the brain, to the management of conditions such as stroke and traumatic brain injury in adults. Photonics technologies can also help to understand the mechanisms of a disease, for example, neurovascular coupling in Alzheimer's disease. In addition, photonic techniques can help during rehabilitation of brain-injured patients and track brain plasticity. Furthermore, being safe and relatively inexpensive methods, they could be utilised to study large, healthy populations to better understand the effects of healthy ageing and brain development. A major challenge is to bring these technologies to the level of maturity needed for clinical application. This requires improvements in signal-to-noise, usability, major reductions in size and cost, standardisation (both of the hardware and associated software algorithms), validation in real settings, integration with other imaging modalities, and expansion for other biomarkers of these diseases.

Photonics technologies offer enormous potential in ophthalmology. © Fotolia

Amongst the prerequisites for general health and well being are clean water, air and soil, and safe food, free from chemical pollutants or biological contaminations.

Environmental monitoring, food and drug quality and safety: Amongst the prerequisites for general health and well being are clean water, air and soil, and safe food, free from chemical pollutants or biological contaminations such as pathogens and their associated metabolism products. The same multi-band photonic and spectroscopic methods and techniques being developed for medical screening applications could, with some modification and adaptations, be employed for monitoring the environment and the quality and safety of food. A recent example of such widespread food poisoning was the 2011 outbreak in Germany, caused by a certain strain of the bacterium Escherichia coli causing a hemolytic-uremic syndrome. In addition, the techniques and methods could also be employed to advance the process analytical technology (PAT) initiative, the aim of which is to allow the in-situ analysis of specific process parameters identified as being critical for drug and food manufacturing, allowing any necessary process adjustments to be applied during manufacture, thereby ensuring quality and efficiency.

Expected impact for Europe

It was the optical microscope that first revolutionised our knowledge of the origin of diseases, and provided an instrument not only to detect diseases, but also to find cures for many. Although the diversity of challenges for good health has yet to decrease substantially, the versatile nature of photonics offers enormous and unparalleled potential to meet these challenges, much of which has yet to be fully exploited.

Photonics technologies can be employed to ensure drug quality and safety for European society. © Fotolia

With predictions of double-digit growth, Biophotonics is a vibrant and promising market.

Each year 12 million new cancer cases are detected, a number that is likely to rise steeply over the coming years, as a direct consequence of demographic changes. Correspondingly, the annual number of deaths caused by cancer is likely to increase from 7.6 million in 2007 to 17.5 million in 2050. According to the WHO, early detection could reduce the mortality by 30%, and Biophotonics offers the powerful tools needed for achieving this.

Similar figures apply to most other age-related diseases, such as Alzheimer's, cardiac infarction, stroke and age-related macular degeneration. For example, recent statistics indicate that cardiovascular diseases, including both ischemic strokes and cardiac infarction, cost the EU approximately €192 billion in 2006, made up of €110 billion for health care costs (about a fifth of the total costs) and €82 billion for lost productivity. Cardiovascular diseases cause 48% of deaths in Europe, and strokes are the second most common cause of death in Europe. In-patient hospital care for stroke victims accounted for about 80% of the total health care costs. We have highlighted this challenge because photonic neuro-monitoring and imaging has tremendous potential for reducing these costs. Other health care issues showing significant increases, which could also be addressed by photonic neuro-monitoring, include traumatic brain injury and Alzheimer's disease, both of which result in substantial financial and social costs in the EU.

Biophotonics has great potential to mitigate many of the health-related consequences of our ageing society, and thus secure our future health, well-being and mobility, as concluded by the Counsel of the EU on innovation in the medical device sector (2011/C 202/03). A further result of the demographic change is that the elderly dependence factor will increase, meaning that more people aged above 65 will have to be supported by fewer working age people. As global healthcare expenditures are also expected to grow disproportionately, this means that working age people will have to bear significantly higher financial burdens. Photonic technologies can help absorb some of these burdens, offering a potential 20% cost reduction [5].

With predictions of double-digit growth, Biophotonics is one of the most vibrant and promising of markets. Increasingly, component manufacturers are addressing this market and aligning their products with the requirements of systems and whole solution providers, thus generating additional synergies. The size of the worldwide healthcare market for optical technologies alone was estimated to be €23 billion in 2010, and to be growing at an 8% CAGR by 2015 [6], with substantially large potential leverage effects. Europe's share of the market currently amounts to about a third. While Europe already has a large share in the microscopy market (>50%), there is scope for significant expansion in the areas of medical imaging and laser therapeutic systems (market share currently ~30%), and especially for in-vitro diagnostic systems (currently below 20%) [7]. Therefore, joint efforts and well-directed funding are the correct instruments to strengthen market positions and generate growth and new job opportunities in this important field.

5 Photonics21 Strategic Research Agenda *Lighting the way ahead*, page 110

6 Photonics21 Strategic Research Agenda *Lighting the way ahead*, page 94

7 Optech Consulting, 2007. From the report *Photonics in Europe, Economic Impact*, published by Photonics 21

Roadmap for 2014–2020

	2014/2015	2016/2017	2018/2019	2020
Technological Challenges	Development of reliable low-cost photonic-based screening methods that allow a fast risk assessment of age and life-style related diseases.			Next generation analytical (multi-band photonic/ spectroscopy based), low-cost and fast methods to control water and food safety/ quality.
		Improved analytic (multi-band photonic/spectroscopic) methods or combination of photonic with non-photonic technologies, which allow further analysis of positively screened persons more reliably and precisely than with current gold standards.		
			Improved, safer and personalised treatment (therapy and monitoring) based on multi-band photonic techniques and methods or on combinations of photonic and non-photonic modalities.	
Research actions (Which solutions should be investigated?)	Photonic based mobile point-of-care devices with high user friendliness and the following specifications: ■ High sensitivity, specificity and accuracy, with high reliability and speed ■ Robustness ■ Safe to operate ■ Low cost ■ Compliant with regulations	New and innovative multi-band photonic and spectroscopic imaging methods and devices (including endoscopes) using multi-modal approaches, that are either label-free or based on already safety-approved labels to further analyze age and life-style related diseases like cancer, cardiovascular and eye diseases and various neuro-pathologies.	Photonics-based highly targeted therapies and continuous monitoring of therapeutic success (also based on other therapeutic approaches). Next generation of Biophotonic methods and tools to understand the origin of diseases.	Next generation photonic based analytical devices for environmental/food quality and safety applications with the following specifications: ■ High sensitivity, specificity and accuracy with high reliability and speed ■ Robustness ■ Safe and easy to operate ■ Low cost

	2014/2015	2016/2017	2018/2019	2020
Innovation actions	Photonic based mobile point-of-care devices.	Multi-band photonic and spectroscopic imaging methods and devices (including endoscopes), multi-modal approaches.	Photonics-based highly targeted therapies and continuous monitoring of therapeutic success.	
Research and innovation requirements (Instruments) Pilot and demonstration actions to involve end users of the value chain Market potential Appropriate innovation models (open innovation, social innovation etc.)	Involvement of medical device manufacturers, pharmaceutical industry (PAT initiative) and clinicians is mandatory. Market potential: Aimed at low cost, point-of-care devices that should be made available to all European citizens through clinics, doctor's practices and even for home-use.	Involvement of medical device manufacturers and clinicians is mandatory. Market potential: The devices are aimed at an employment in clinics and in doctor's practices at costs that are comparable to today's equipment.	Involvement of medical device manufacturers and clinicians is mandatory. Market potential: The techniques and devices are aimed for an employment in clinics.	Involvement of public procurer (e.g. public institutes responsible for environment and food safety). Market potential: Aimed at low cost and mobility, the devices should find broad and universal applicability.
Cross-cutting Key Enabling Technologies (KET) issues Pilot and demonstration actions Synergies with other KETs	Pilot action for mobile point-of-care screening devices together with KET 'Nanotechnology' including enabling technologies for point-of-care devices such as, for example, microfluidics.	Pilot action for new and innovative multi-band photonic and spectroscopic imaging devices together with KET 'Nanotechnology'.	Outreach to Health insurance providers and medical device manufacturers (KET 'Nanotechnology') as well as physicians and clinicians for the deployment of Biophotonic technologies in health. This includes actions for classification of products and standardisation. Pilot action for low-cost and fast analytical methods for process analytical technology (PAT) initiative together with KET 'Biotechnology'.	Pilot action for low-cost and fast methods to control water and food safety/quality which are close to commercialisation together with KET 'Biotechnology'.

2.4 Emerging Lighting, Electronics & Displays

Main socio-economic challenges addressed

This topic deals with a broad palette of interrelated photonics technologies, each showing different times to market, notably, LED (Light Emitting Diodes), OLED (Organic Light Emitting Diodes), OPV (Organic Photovoltaic), Flexible Electronics based on OLAE (Organic Large Area Electronics) and Display technology.

Each of these technologies offers substantial contributions towards solving the grand societal challenges defined by the European Commission:

- Displays for medical diagnostics, SSL (Solid State Lighting) offering the optimum lighting conditions for lack of daylight, and Flexible Electronics unlocking personalised diagnostics and treatment, will impact *Health, demographic change and well-being*.
- SSL reducing lighting energy consumption by a factor of three, and OPV generating clean energy locally, will substantially contribute to *Secure, clean and efficient energy* and indirectly to *Climate action, resource efficiency and raw materials*.
- OPV integrated into cars and SSL road lighting as part of traffic management systems will play a role in the realisation of *Smart, green and integrated transport*.
- Innovative Human Machine Interface using Flexible Electronics, and Display technology for rich visual information everywhere and at any time, will be highly instrumental in the realisation of *Inclusive, innovative and secure societies*. It is indisputable that ubiquitous connectivity will be a prerequisite for making this happen.

Innovative uses of OLED lighting – the living mirror. © Philips Lighting B.V.

Major photonics needs

The market share of LED technology is rapidly increasing, and it is projected to become the dominant lighting technology before the end of the decade. This change in technology will allow the business to transition from light sources to intelligent lighting solutions. While the present added value of intelligent lighting clearly rests with its energy saving and the consequent reduced carbon footprint, most people are still reluctant to commit themselves to this technology because of the lack of a convincing proof of its economic viability. Furthermore, the benefits of lighting on health and well-being are anticipated to generate even more added value, and so justify further investigation.

The major added value of intelligent lighting results from its significant energy savings and consequent reduced carbon footprint.

The sustained research efforts over recent years have resulted in a steady increase in performance of both OLED and OPV technologies. For these now to become competitive with LED technology and Si-PV (silicon based photovoltaic) technology respectively, a clear breakthrough in cost perfor-

By acting as a launching customer for SSL, public authorities will be able to benefit directly from the savings offered by this technology.

mance ratio will be needed, requiring, amongst other things, a massive investment in production equipment.

The development of Flexible Electronics is now offering a variety of new functionalities, having the potential to open up a completely new branch of industry. This European industry will be built around a large number of SMEs, each of them targeting specific application domains with their customised devices, complemented by existing large companies. Flexible Electronics will also unlock innovation in traditional industry segments, such as printing, plastic moulding, paper, and even textiles. In order to respond quickly to the demands of the market, all these companies will need access to flexible production facilities. Considering the current limited availability of financial resources, such capital investments will present a clear challenge.

Despite the display market being dominated (in terms of production volume) by players from Asia Pacific, Europe has maintained its position of strength in material supply, production equipment and visualisation systems. The display industry is currently shifting its focus from LCD (Liquid Crystal Display) towards OLED technology for direct-view displays, from lamps towards LEDs for micro-displays, and towards high brightness LEDs or solid-state lasers for projection displays. 3D displays that do not require special viewing glasses will be the next step in televisual experience, ultimately enabling remote collaboration. This will require the development of display systems showing a resolution exceeding that of current HDTVs by at least a factor of 100. The ubiquitous presence of displays will continue to create profitable niches, answering different needs throughout the European market.

OPV contribute to energy creation. © Holst Centre

Involvement of Value Chain Partners

With respect to energy efficiency and carbon footprint reductions, the involvement of public authorities will be critical for pinpointing the added value offered by SSL technology (encompassing LEDs and OLEDs). Indeed, public authorities own a substantial part of the existing infrastructure for both indoor and outdoor lighting, so, by acting as a launching customer for SSL, public authorities will be able to benefit directly from the savings offered by this technology. Additionally, guided by the early feedback from the initial launching customers, the SSL industry will be able to achieve a much faster rollout of this technology.

Fragmented information on the effect of incumbent lighting technology on people's health and well-being is already available. However, with the advent of SSL technology the spectral, spatial and temporal distribution of lighting can be readily adjusted, offering as yet unexplored new opportunities. To investigate and better understand how tailored lighting conditions could impact the health and well-being of people, the direct involvement of end-users and experts will be required, the latter drawn from the fields of medical science, gerontology, psychology and sociology. In addition to its impact on humans, tailored lighting conditions could also affect animals and plants. Therefore, close collaboration with experts from the biological and agricultural domain will be essential, allowing the potential impact of tailored lighting on the reliability and efficiency of global food supply to be assessed.

The building of a manufacturing infrastructure for OLED, OPV and Flexible Electronics will require close collaboration with both production equipment industry and material suppliers, so as to ensure that the essential requirements for speed, cost and flexibility can be met.

OPV offers significant advantages over Si-PV for the direct integration of energy generation into building components, and it is expected to play a major role in facilitating the creation of urban systems around solar energy. Close collaboration with the building industry must be established to maximise the exploitation of this market opportunity.

Breakthrough innovations in Flexible Electronics will result from close collaboration with system integrators and product designers. The development of 3D display systems will be closely dependent on the rollout of ubiquitous high-bandwidth access infrastructure. As a result of its proximity to world leading companies in relevant application fields, such as automotive, avionics, space technology and medical science, the European display industry will be able to make the transition from components towards supplying full visualisation systems. The massive market uptake of intelligent display systems will also depend strongly on the industry's ability to interact with the user.

Major Photonics Research and Innovation Challenges

LEDs

As indicated above, the lighting industry will go through a transformation from a supplier of replacement lamps to the provider of intelligent lighting systems, putting the user at the centre of the solution. This also implies that lighting will no longer be seen as a commodity, but instead as a customised solution, adding value to people's lives.

Many challenges still need to be addressed across the full value chain, from materials right through to lighting systems. With the advent of a new lighting technology, ideal conditions will exist for embedding C2C (cradle to cradle) concepts fully within the lighting domain, driving design for recyclability. At the LED level, research efforts dealing with cost, light quality and efficacy must be continued. Cost and performance in the short term are also major issues at the lamp and engine level, while the continuing standardisation efforts will contribute significantly to the adoption of LED technology by the predominantly SME luminaire manufacturers. Standardisation will also be needed in the field of two-way communication between the various system components, the use of indoor DC grids, the integration of lighting systems into the built environment, and its interaction with the smart grid. Interoperability of the various system components will be critical for market uptake of digital lighting. Specific architectures, tailored to the needs of different market segments, must be developed to allow for the seamless integration of different components within the lighting system, and for the integration of lighting with other functions in smart buildings and communities.

Low-energy LED lighting in an office installation.

The future of the lighting industry largely depends on its ability to make the transition from light sources to intelligent lighting systems, enabled by Solid State Lighting (SSL), that is, LEDs and organic LEDs

The future of the lighting industry largely depends on its ability to make the transition to new intelligent lighting enabled by Solid State Lighting.

LED illumination at the Bucerius Art Forum, Hamburg, Germany. © OSRAM GmbH

(OLEDs). This requires close collaboration with the micro-electronics industry to develop new system architectures, including hardware and software architectures and interfaces suited for lighting systems, and in close relation with their (new) applications. Most of the existing ICT architectures are built around the exchange of massive data streams between a 'limited' number of nodes (typically, one per office desk, one to two per home). For lighting management, the number of nodes will be much higher (30 light points per home, 100,000 light points for an average community, with each light points consisting of 50–1000 LEDs which may be driven in even smaller subsets), while the data rates needed per node are much lower. Lighting management based on the existing architectures will consequently come at a high cost, severely hampering the market uptake of this technology and applications. The markets served by lighting are of a different nature, requiring different trade-offs between performance, functionality and cost. Moreover, these architectures are likely to vary for the different application domains: outdoor, office, retail and residential homes.

The full refurbishment of a medium sized European city would provide compelling evidence of the major advantages that LED technology can bring to society.

It is clear that the opportunities for new, value added lighting applications are massive, offering energy savings, superior lighting control for context-dependent lighting, improved quality of light, and increased functionalities such as adaptive lighting. In particular, the effect of lighting on people's health and well-being also needs to be explored, a dimension of lighting seen by industry to offer added value far beyond its immediate energy saving potential. Additionally, SSL could offer exciting new opportunities in crop growth (green houses and city farms), cattle breeding, and fish farming.

The major challenge in the LED domain however is expediting the anticipated massive uptake of intelligent lighting by the market. Whilst other regions have placed their primary emphasis on replacing existing light sources by LED retrofits, the European lighting industry is convinced that intelligent lighting offers greater commercial and ecological benefits. Far greater energy savings can be achieved by combining LED technology with advanced controls, and can also generate significant added value beyond energy saving alone. To speed up its uptake, market demonstration and validation will be essential, and at a level beyond that of existing demonstration projects, which to date have only covered a relatively limited number of light points. The full refurbishment of a medium sized European city would bring compelling evidence of what LED technology can bring to society, and would also showcase the commitment of public authorities to energy efficiency. The vast amount of information that could be gathered from such an action would also act as a springboard for driving the development of building- and district-level energy regulations. Additionally, these large scale demonstration actions also provide a research opportunity, allowing issues related to scalability, system latency, system security, and utilisation due to user behaviour change to be addressed under real life conditions.

The major hurdle facing public authorities considering SSL deployment is the risk that their investments will not yield the anticipated savings. The intervention of the Structural and Cohesion Funds would mitigate those risks for the early adopters, and would be highly instrumental in overcoming this hurdle. In order to implement quickly the results of the Photonics PPP, the EU Commission should consider establishing a revolving fund with the participation of the European Investment Bank, targetting the fast followers.

The recommendations of the task force on SSL for Cities, established by the EU Commission within the framework of the SSL Green Paper ‚Lighting the Future', will be highly instrumental in speeding up the uptake of intelligent LED based lighting in the public domain.

OLEDs (for lighting)

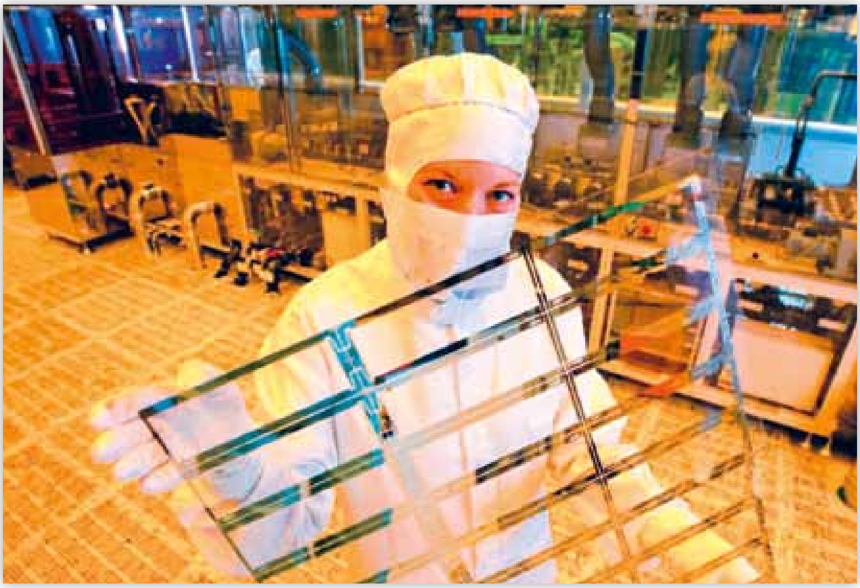
In terms of technological maturity, OLEDs lag behind LED technology, and consequently OLEDs are faced with an LED-dominated market. The penetration of such a market will strongly depend on the OLED's ability to outperform LEDs in two areas; cost performance and the new market opportunities offered by large area and flexible light sources. Material suppliers will be highly instrumental in achieving the required cost performance breakthroughs, as well as for developing efficient blue light emitters and more efficient OPV layers.

These cost performance issues can only be addressed effectively by making the transition from 'lab to fab'. Only when pilot lines are deployed, will it be possible to assess the full potential offered by this technology. The highest throughput and lowest costs come through the use of sheet to sheet (S2S), roll to sheet (R2S), or roll to roll (R2R) processes, together with photolithography or laser ablation. Materials represent a major contribution to the cost of OLED products, and this dictates that effort be focused on production processes with low levels of material utilisation.

In laboratory conditions, limited size flexible OLEDs have been realised on metal and plastic substrates. Now it is necessary to scale up fabrication to the pilot line level, allowing a realistic assessment of their market potential to be made.

OLED light installation Supernova on designer platform lab.me. © OSRAM GmbH

Flexible OLED. © Holst Centre



OLED pilot production line in Regensburg, Germany. © OSRAM GmbH

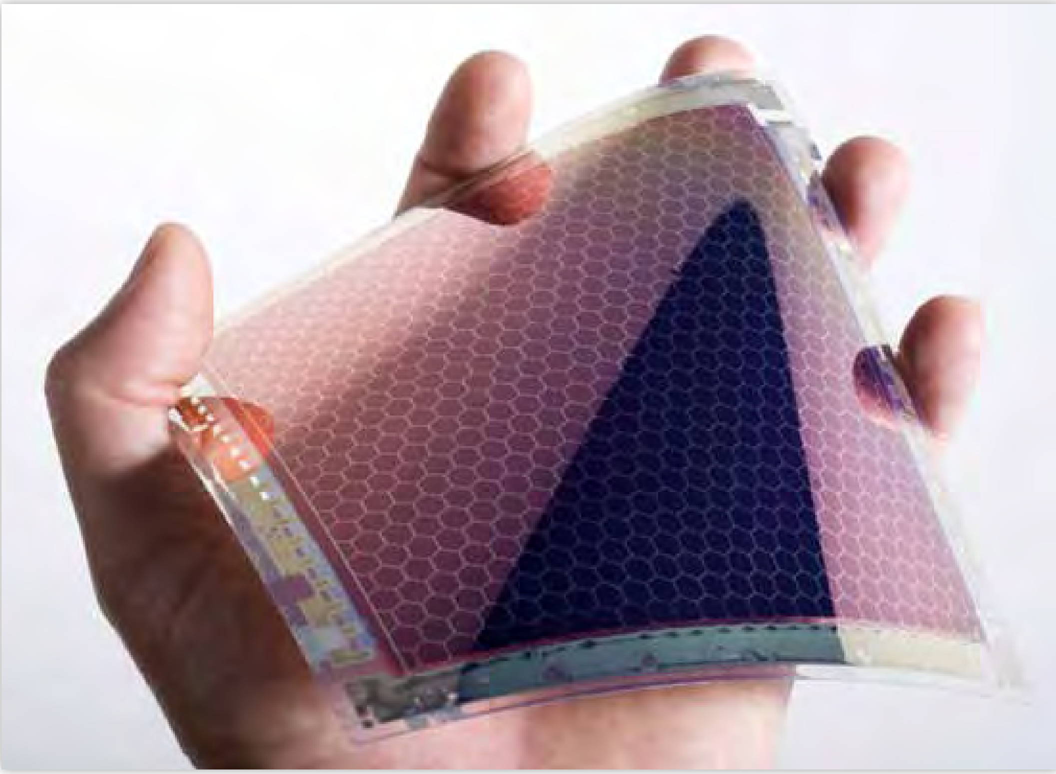
As with LED technology, system integration for creating user-centric solutions will require the development of hardware and software architectures, enabling the interoperability of light sources, actuators and sensors from different suppliers.

OPV

Initially OPV is expected to penetrate dedicated niche markets, subsequently leading to serving new volume markets. A notable example of this would be providing energy to the 1–2 billion people in the world, who will never have direct access to an electricity grid. This could be the perfect stepping-stone for this technology, exploiting the exceptional robustness offered by OPV in comparison to conventional photovoltaic technology. Future mass markets are anticipated to lie with e-mobility and with building-integrated photovoltaics, which are both application fields that will profit significantly from conformable, flexible and transparent solar cells. The European Photovoltaic Industry Association (EPIA) predicts that this massive market uptake of OPV will occur around 2020, allowing sufficient time for OPV technology to improve and outperform conventional Si-PV technology.

A doubling of the present efficiency of the OPV is being targeted.

The innovation challenges facing OPV are very similar to those facing OLED lighting technology. Major improvements in the cost performance ratio will be required to become competitive with the established Si-PV technology. To achieve this, a doubling of the present efficiency will be needed, as well as a substantial increase in lifetime, and these targets must be high on the research agenda. New materials will play a major role in achieving these improvements. In parallel with this, scaling up fabrication from cells to modules, and the transition from 'lab to fab' to manage the complexity of the processes, will both make a major contribution to cost reduction. However, this goal can only be reached though a substantial increase in investment in pilot production facilities. There are clear opportunities for cross-fertilisation between the technologoies developed for the OLED lighting and



It is estimated that a massive market uptake of OPV will occur around 2020. © Holst Centre the OPV industries. For example, whilst OPV will evidently benefit from mass-production methods developed in the OLED industry, the roll-to-roll processes developed for OPV could also benefit the OLED industry.

Flexible Electronics based on OLAE devices

Cheap, mass-produced smart systems built around organic, flexible and large-area electronics will create many new business opportunities. These will make use of what is termed 'human size electronics', as well as advanced man-machine interfacing. Examples include electronic labels for logistics, smart packaging, personalised health diagnostics, and medical therapy. To date, most attention has been given to the realisation of generic OLAE devices, but the heterogeneous integration of proven functionalities into systems will pave the way towards industrialisation. Initially these devices will integrate simple functionalities using the existing infrastructure with proven integration technologies. In a subsequent phase, multiple functionalities will be integrated in conformable and flexible systems, requiring new processes and more advanced heterogeneous integration approaches. Most of these innovative devices will include large area photonics devices, such as displays, lighting elements, OPV and photonics sensors.

The first steps for creating open prototyping and small series production facilities have already been made. The recommendations of the COLAE (Commercialisation clusters of Organic and Large Area Electronics) co-ordination and support action will be instrumental in rationalising the existing European production infrastructure. This rationalisation effort should be strengthened to offer start-up companies, existing SMEs and fabless design houses, the opportunity of exploring the full market potential of their product ideas. Although modelling and simulation tools are readily available for silicon-based devices, these are not suitable for complex heterogeneous Flexible Electronics devices. The development of such tools will be essential for achieving a short time to market for new Flexible Electronics devices.

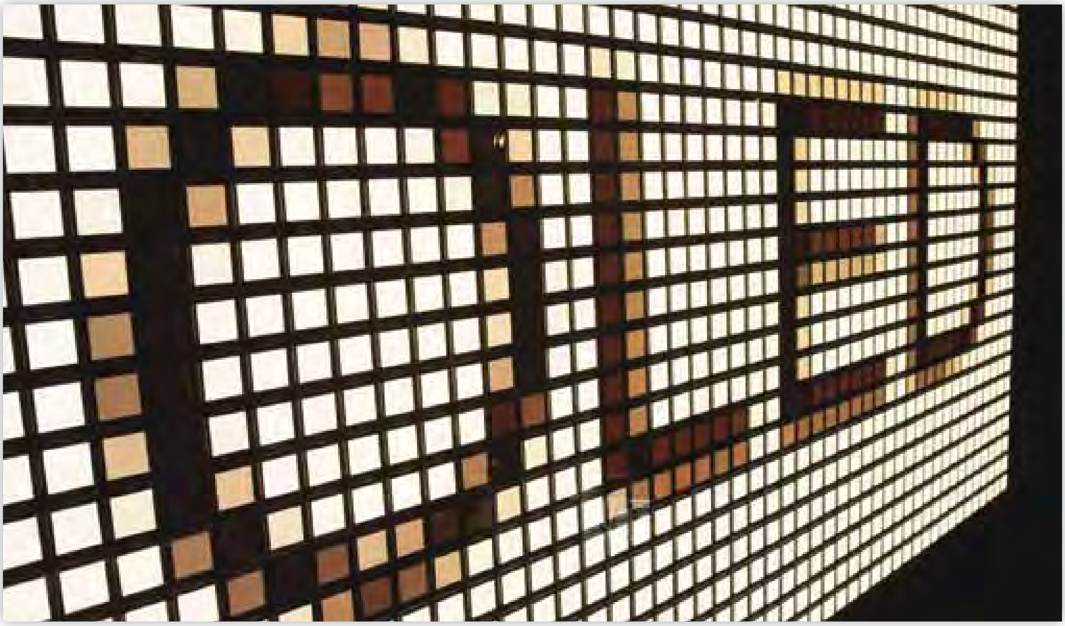
Displays

Displays are one of the most visible expressions of photonics as a key enabling technology. High-fidelity visual communication will increase efficiency and competitiveness, in particular for high added-value applications for remote collaboration between professionals, for example, engineers, business executives, medical doctors, etc. The display demands are very heterogeneous and the preferred display technology will depend largely on the specific end-application, for example, direct-view AMOLED (active matrix OLED), e-paper, projection displays, and near-to-eye displays.

A high priority has been assigned to the development of technology for AMOLED displays because, when compared to conventional liquid crystal displays, this technology is potentially superior in overall image quality, thickness, power efficiency and weight, and all achived at lower manufacturing cost. Research topics are focusing on improvement of the metal oxide TFTs and organic TFTs, new OLED and film materials for longer lifetime, increases in wall plug efficiency, and the development of curved, flexible and rollable displays.

Specifically for near-to-eye micro-displays, the main challenges include achieving high luminance at reduced pixel size, as well as power reduction. Research topics should therefore focus on new lighting structures and materials, on the optimisation of colour generation, and on new packaging technologies, including improved thin film encapsulation.

The glasses-free 3D display system with >100 views, needed for a truly immersive experience, will require large bandwidth access at the network endpoints. A rich immersive visual experience requires life-size displays with a resolution corresponding to nominal visual acuity. There is a



Large area intelligent OLED lighting used for interactive displays. © Philips Lighting B.V.

steady move towards these targets with increases in the number of views and improved resolution for the displays, and constantly improving network bandwidth and latency on the systems side. Product development and manufacturing need to focus on the integration of sensors. Glasses-free 3D displays will also require the development of a specific production infrastructure for the alignment of different views and testing of the overall experience. In addition to 3D displays themselves, immersive experiences require the integration of visual and auditory capture, haptic feedback, control software, and processing components. The building of a first-of-a-kind true 3D demonstrator will contribute greatly to the development of such a production infrastructure.

New advanced materials and nano-materials will lead to major improvements in OPV, OLED and Flexile Electronics devices.

Synergy with other Key Enabling Technologies

For all above-mentioned applications, it is essential that the development of photonics technologies be closely aligned with the latest developments in microelectronics technologies. This will allow the adoption of optimum approaches for driving SSL efficiently, managing and monitoring energy usage of lighting systems, driving the display content, and integrating the photonic and flexible electronic devices into larger ICT (Information and Communication Technologies) systems.

Furthermore, new advanced materials and nanomaterials will contribute greatly to the improvement of all the photonics devices discussed. This is particularly the case for OPV, OLED and Flexile Electronics devices.

In addition to this synergy with other key enabling technologies, it would be beneficial if, within the photonics KET, a closer collaboration between the SSL industry and the optical sensor industry were established to speed up the introduction of intelligent lighting systems. Further, by teaming up with life science and health sector, innovation in the domain of flexible electronics for personalised diagnostics and treatment would be greatly accelerated.

The following table shows the major innovations actions identified for this technology sector. They are the logical consequences of actions already commenced in the FP7 framework programme. The timing of each of these actions is chosen so

Roadmap for 2014 – 2020

<table>
<tr><th></th><th>2012-2013</th><th colspan="2">2014-2015</th><th>2016-2017</th><th>2018-2019</th><th>2020</th></tr>
<tr><td>LED</td><td>R Smart lamps & modules
CSA Biological efficiency</td><td colspan="2">LSD Intelligent lighting for cities
R Open system architecture
R Biological efficiency</td><td>R Biological efficiency</td><td rowspan="2">S&R Building code</td><td></td></tr>
<tr><td>OLED</td><td>R Cost-performance breakthrough</td><td>P&MS High-speed production facility for flexible OLEDs</td><td rowspan="2">R Materials for cost performance</td><td></td><td>R Open system architecture</td></tr>
<tr><td>OPV</td><td>R Cost-performance breakthrough</td><td>R Off-grid solutions</td><td>P&MS Adaptable low-cost high-speed production facility</td><td>R Integration into building components</td><td></td></tr>
<tr><td>Flexible Electronics</td><td>R Heterogeneous system on foil
CSA COLAE</td><td colspan="2"></td><td>R Modelling & simulation tools</td><td>P&MS Adaptable open-access production facility</td><td></td></tr>
<tr><td>Displays</td><td></td><td colspan="2">R systems for ultra-high performance and viewing experience
R materials & and processes for high performance displays</td><td>P&MS Upscaling of performance materials and processes</td><td>FoKD 3D glasses-free multi-view (> 100 views)</td><td>P&MS 3D glasses-free multi-view and near-to-eye displays</td></tr>
</table>

Key:

CSA	Co-ordination & support action	**LSD**	Large-scale demonstration & market validation action
R	Research project	**FoKD**	First-of-a-kind demonstration action
P&MS	Pilot production & market sampling	**S&R**	Standardisation & regulation action

as to build on the results of these previous actions, and on the synergies existing between the different technologies.

Market validation should be an integral part of innovation projects, irrespective of whether their focus is on applied research or on piloting. In some cases, the cost of demonstration and validation will be too high to be integrated in such actions. Therefore two new types of instruments are proposed, First of a Kind Demonstrations, targetting complex systems, and Large-scale Demonstration & Market Validation Actions, complementing the existing demonstrations within the CIP programme.

Expected impact for Europe

In the near future, solid-state light sources (LEDs and OLEDs) will outperform all other light sources in terms of efficiency, and will achieve potential energy savings up to 30–50%. A further 20–50% could be saved if SSL technology is combined with intelligent light management systems that regulate light output according to ambient lighting conditions or people's presence and activities. Overall therefore, advanced SSL could cut present-day electricity consumption for lighting by about 70%.

Advanced SSL systems could cut present-day electricity consumption for lighting by about 70%.

The realisation of such digital lighting solutions would result in huge benefits [8]:

- more than €300 billion saved annually on the global energy bill
- global reduced emission by more than 1000 million tonnes of carbon dioxide per year
- the economy boosted by strengthening Europe's industrial position in lamps, luminaires and driver electronics, which together already employ over 150 000 people
- society at large benefiting from the greater visual comfort of superior lighting solutions, and reduced light pollution through more closely focused lighting
- significant individual savings from energy-efficient lighting technologies

Recent projections by the European Lighting Industry (ELC-CELMA) indicate that by 2020 more than 95% of lighting turnover will be based on SSL technology, equating globally to €52 billion for luminaires and €12 billion for lamps and lighting engines. These figures indicate a ten-fold increase in LED luminaire sales and a four-fold increase in LED lamp sales compared to present levels. Comparable figures for the EU27 show similar growth rates at €18 billion and €4 billion respectively.

The OPV market is predicted to grow to €630 million by 2022, though still representing less than 1.5% of the predicted total PV market. However, around that time OPV is expected to have reached sufficient maturity to allow for direct integration into building materials, thereby opening up a huge mass market. By 2016 the world market for rooftop building integrated photovoltaics (BIPV) is predicted to reach €2 billion, and the market for wall integrated PV to reach €1 billion. The latter market will profit greatly from the advent of OPV, and is expected to exceed the existing Si-PV market by a factor of at least 10.

The present Si-PV off-grid market is approximately €2.4 billion with an estimated CAGR of 9–15%. Conservative estimates indicate that the off-grid OPV market could easily match this value.

Flexible Electronics based on OLAE devices are expected to enable completely new markets, offering large business opportunities to specialised start-up companies, as well as to existing large electronics companies. Additionally, Flexible Electronics will also drive innovation in the more traditional paper and plastic industries. As with all emerging technologies though, the prediction of reliable market forecasts is difficult, particularly because Flexible Electronics could impact so many market segments, including consumer goods, building components,

8 *ICT for Energy Efficiency*, DG-Information Society and Media, Ad-Hoc Advisory Group Report

transport, healthcare, gaming, packaging & logistics, food, and pharmaceutics. Specific information on the consequent economic impact in terms of either turnover or job creation is therefore not currently available. However, the overall OLAE market, including Flexible Electronics devices, OLED lighting and displays, and OPV, is expected to grow from its present value of €1 billion to between €100–200 billion, depending on the source consulted.

Display-enabled rich visual communication will trigger the next communication revolution for professional users, offering attractive alternatives to the less effective collaboration tools of today, thereby avoiding the need for many travel-intensive, face-to-face meetings. In Europe alone, this is expected to result in a 20% reduction in business trips, saving 22 million tonnes of CO_2 emissions per year. At the same time, the deployment of such systems will contribute directly to increased productivity in several other markets, especially in the service sector. This sector alone generates 75% of the EU GDP, and increased productivity accounts for 50% of its annual growth. Europe is ideally placed to establish a leadership position in this sector, being home to many of the largest system integrators and having unique strengths in end-user centric and application-driven design.

As well as the advanced 3D displays themselves, additional components will be required to create a rich visual experience for the user. The business multiplication effect thus generated is estimated to be a factor of 3 for the low-end segment, rising to a factor of 10 for the high-end segment. It is estimated that global sales of advanced 3D displays will reach €10 billion by 2021, with a 35% share for European companies, and a show CAGR of 15% over the period 2021–2025. This will increase the overall annual turnover to some €36 billion by 2025. The realisation of this ambition will require the development of a European eco-system. The development of such systems will require high-quality advanced engineering as well as the involvement of experts in the fields of psychology, sociology and user experience. This is expecetd to generate approximately 5000 highly qualified new jobs in science and engineering. Also, the job creation in production is predicted to reach 14 000, along with an additional 28 000 jobs in sales and services.

In the short term, the Photonics PPP will contribute greatly to the consolidation of the European lighting industry's current number one position, and further offers the opportunity to outpace the competition from other regions through focussing on the added-value lighting, rather than cost alone. In the longer term Organic Large Area Electronics has a huge potential to build new businesses and new jobs for Europe.

Left: Energy-efficient buildings rely on innovative lighting installations and concepts. © Fotolia

Right: Immersive visualization systems to support professionals & scientists, here at RWTH Aachen. © Barco nv

2.5 Security, Metrology & Sensors

Main socio-economic challenges addressed

Optical methods will provide breakthrough solutions for sensing hazardous substances.

Today, over 70 million organic and inorganic substances are on record[9], and for most of these, little is known about their potential danger to humans. Although only a small fraction of this plethora of molecules are marketed and released into the environment, our society is confronted daily with a growing number of potentially hazardous chemicals.

Well-known examples of the reality of this threat include the contamination of milk with melamine, of drinking water with herbicides and fungicides, of wine with glycol, and of plastic food containers with hormone-like components (endocrine disruptive compounds). As a result, increasingly and often justifiably, our citizens feel threatened by potential hazards contained in the foodstuffs they eat and drink, and in the air they breathe.

The WHO estimates that more than two billion illnesses are caused by unsafe food every year.

Much worse, naturally occurring molecules, produced by microorganisms within our food, represent an even larger threat to our society's health. The WHO estimates that more than two billion illnesses are caused by unsafe food every year, and in the developing world alone, two million children die annually from contaminated food and water[10]. In Western countries, 5–10 people per million inhabitants die every year from food borne diseases[11]. In the USA alone, this claims an annual death toll of more than 3000 people, costing up to $35 billion in medical costs and lost productivity[12].

Already today, we possess the biochemical and technical means to identify small numbers of molecules or microbes in a sample. However, all these methods are expensive and time-consuming. Optical methods may provide breakthrough solutions to this highly relevant problem, overcoming the traditional, tedious chemical lab analysis. For example, it is known that measurement techniques in the mid-infrared (MIR) spectral range, known also as the fingerprinting/diagnostic region, are highly specific to individual molecules, even able to distinguish between isotopes in their atomic constituents. Optical methods can also be extremely sensitive, exploiting the existence of photonic sensors capable of detecting the arrival of single photons with sub-nanosecond timing precision. Additionally, very sensitive and highly specific novel diagnostic techniques are emerging, such as Raman and LIBS spectroscopy, whose performance would be much improved if operation could be extended into the infrared spectral range. However, the major problem with the current photonic devices and detection systems capable of achieving the required specifications is that they are much too expensive for the realisation of affordable, practical sensing systems! Consequently, if the challenges described above for food/air/water/environmental safety and security, are to be solved, it is essential that multiband photonic sensing is developed, leading to a safer and more secure society. Once available, these photonic innovations will lead to numerous additional applications, further improving many aspects of our daily lives.

Major Photonics needs

The near infrared (NIR) spectral range (0.8–2.5 µm) is already employed for many tasks in food inspection (moisture sensing, content of protein/

9 On-line Registry of the Chemical Abstracts Service (CAS) of the American Chemical Society: http://www.cas.org

10 WHO Reports on Food Safety Issues, *WHO Global Strategy for Food Safety: Safer Foord for Better Health*, World Health Organization, Food Safety Department, Geneva (Switzerland) 2002, ISBN 92 4 154574 7

11 D. Pimentel et al., *Ecoloy of Increasing Diseases: Population Growth and Environmental Degradation*, Hum Ecol Vol. 35: 653–668, 2007

12 Wikipedia article on Foodborne Diseases: http://en.wikipedia.org/wiki/Foodborne_illness

Photonic technologies can help retailers and customers to judge the ripeness of fruit and vegetables, and so reduce the percentage of discarded food. © Fotolia

Photonic measurements are used for the screening of water for contamination. © Fotolia

oil/fat/starch/sucrose/fibres, detection of foreign particles and nut/fruit-stone inclusions, quality and ripeness of fruit and vegetables, etc.), as well as in recycling and waste treatment (sorting of wastepaper, cardboard, plastics/polymers, fuels, industrial waste). The diagnostic mid-infrared (MIR) region (2.5–7 µm) yields information about the presence of functional groups in samples, enabling, for example, the identification of numerous volatile organic compounds (VOCs) in gases. The fingerprint MIR region (7–11 µm) allows the different compounds in a sample to be distinguished, due to the specific spectral 'fingerprint' of each molecule in this spectral domain, utilising the large existing collections of reference spectra in vapour and condensed phases. Finally, the far infrared and THz region (up to 1000 µm) offers complementary fingerprinting capabilities using specific spectral signatures, with the additional benefit of deep penetration in standard packaging materials such as paper, plastics or textiles.

Some of these critical measurements in the extended infrared (EIR) spectral domain (1–1000 µm) can be performed today, albeit with very expensive active and passive photonic components. For example, a moderate-power MIR laser costs €10,000, an uncooled FIR bolometer camera costs at least €50,000, a 128x128 NIR image sensor (InGaAs) costs €4000, a single photodiode (InAsSb) for the 1–5 µm band costs €1000, and even a single silicon microlens (for wavelengths above 1.1 µm) costs €50. Clearly it is not currently possible to realise cost-effective EIR sensor devices and make them affordable for general use, despite the abundance of highly relevant practical applications operating in the infrared spectral domain. While the important ultraviolet and visible (UV/VIS) spectral domain is accessible using the ubiquitous silicon photosensors, we have to progress beyond silicon in order to meet the challenges of the EIR domain.

The challenge is therefore clear – we need to develop new high-performance yet affordable photonic devices. Specifically:

- quantum-noise-limited active optoelectronic devices (coherent and incoherent sources, detectors) based on inorganic/organic semiconductor materials, offering the appropriate EIR properties.
- CMOS-based charge detector platforms with low-noise/low-power/high-speed-readout performance that can be combined with many classes of semiconductor materials.
- novel measurement techniques to exploit the beneficial properties of such newly developed EIR detectors for industrial applications.
- affordable non-toxic cooling solutions (in particular thermo-electric coolers) for EIR photosensing and light emission platforms
- a wide range of low-cost passive optical components, to enable the integration of complete EIR systems.

The overall goal is to conquer the EIR spectral range with a complete toolbox of low-cost active and passive photonic devices. These will be used to provide reliable, high-performance yet affordable diagnostics measurement methods and systems for professional and consumer use.

Involvement of value chain partners

The development of multi-band photonic sensing will make a huge contribution towards a safer and more secure society.

The challenge of providing such multi-band photonic sensing for a safer and more secure society is enormously ambitious, because true innovation in this highly interdisciplinary domain requires exceptional science and engineering capabilities combined with advanced production skills.

The materials challenges are significant, and a close collaboration with the KET Advanced Materials will be essential for solving them. In particular, the necessary inorganic/organic optoelectronic materials are not very common, the demands on inorganic crystalline purity are very high, and only a few organic semiconductors are known possessing a cut-off wavelength above 1 µm. Additionally, efficient thermoelectric cooling requires new novel material systems that will be affordable and non-toxic, yet very few alternatives to today's bismuth tellurides have been commercialised to date.

Certain materials required for NIR/MIR active optoelectronic devices must be formed as nanoparticles to be effective. Also, an important class of MIR lasers and detectors employs the quantum cascade mechanism, requiring precise design and fabrication of hundreds of nanometer-thin layer structures. To solve these nano-engineering challenges, collaboration with the KET Nanotechnology will be critical.

Usually the production cost of optoelectronic devices is dominated by the packaging process, and not by the employed materials themselves. To minimise such costs, the techniques and fabrication facilities developed for microelectronics have and will be used wherever possible for photonic device fabrication. Consequently, this has resulted in very close ties with the KET Micro- and Nanoelectronics.

Photonics is essentially a three-dimensional challenge, and current microelectronic planar fabrication methods have only limited capability to be extended into the third dimension. Precise, low-cost photonic microsystems require novel, cost-effective, 3D fabrication methods. These combine a very high degree of integration with a minimum number of assembly steps, inherently providing the micron/sub-micron resolution necessary for photonic microsystems. Therefore, close collaboration with the KET Advanced Manufacturing will be essential.

Finally, a key element for any successful innovation process is the early involvement of potential application partners, so as to ensure that the designed systems really meet the specifications and expectations of the end users. A vast range of application domains is anticipated for the envisaged multiband sensor technologies, so early contact with several of Europe's Technology Platforms (ETPs) will be necessary to ensure systematic and coordinated goal setting, R&D activities, and practical verification. These include specifically, the ETPs for Nanomedicine, Food, WSSTP (Water Supply and Sanitation Technology), GAH (Global Animal Health), SMR (Sustainable Mineral Resources), EuMaT (Advanced Engineering Materials and Technologies), EPoSS (Smart Systems Integration) and Industrial Safety.

Major photonic research & innovation challenges

The guiding principle for all the envisaged R&D efforts is to achieve affordable effectivity for the measurement task. For example, it is pointless to develop an EIR laser source with record quantum efficiency at a wavelength, for which no high sensitivity photodetectors are available. For all components of a complete photonic measurement system, a sensible cost-performance balance must be identified, so that the resulting system solves the given measurement task in a reliable and affordable manner.

EIR sources

As a consequence of the low concentration of many critical analytes, there is a huge need of cost-effective, narrow-band, medium-power (1–100 mW) light sources, allowing the measurement process to be done quickly and with the required resolution. Of particular interest are solid-state lasers, such as QCLs (Quantum Cascade Lasers), VECSELs (Vertical External Cavity Surface Emitting Lasers), VCSELs (Vertical Cavity Surface Emitting Lasers), and fibre lasers. Since many technologies utilise electronic lock-in methods, it must be possible to modulate the lasers electrically. For stable, efficient operation in the MIR/FIR, the lasers must be cooled and temperature-controlled, and care must be taken that these cooling requirements do not dominate the production cost of the complete laser sub-system. For low-cost laser systems, electrical emission wavelength tuning capability is desirable, with tuning ranges of several 10 nm or up to a few 100 nm.

A specific goal is the development of a family of tunable EIR light emitters. Complete laser system costs, including cooling, modulation control, and electrical power supply, should reduce to a few €100.

Additionally, NIR/MIR light-emitting diodes (LEDs) may be of interest as an alternative source in sensing systems that do not require narrow-band illumination. New and more powerful sources for wide-band IR spectroscopy are also needed, such as those based on fibre supercontinuum effects, offering convenient coupling to optical fibres. Here the goal is the development of NIR/MIR broadband light sources offering emission powers ≥1 mW, with ≤ €1 cost in large volumes.

EIR photodetectors (0D, 1D, 2D)

A large number of materials and detector types are currently employed for point, linear and image sensor devices for the NIR/MIR spectral range, including pyroelectric detectors, thermopiles, microbolometers, narrow-bandgap photovoltaic detectors, Schottky barrier detectors, extrinsic photoconductors, multi-quantum-well semiconductor heterostructures for QCDs and homo/heterojunction internal photoemitters (HIP). The challenge is to detect as many incoming photons as possible, while reducing the effects of dark current. This corresponds to the primary task of maximising the sensor's detectivity, which is equivalent to minimising its noise equivalent power. At the same time, material and packaging costs must be reduced to increasingly lower values, and cooling requirements kept to a minimum.

The primary goal is to develop novel types of highly cost-effective solid-state NIR/MIR sensors, based on new or optimised material systems, and ideally produced using well-established microelectronic fabrication techniques. It must be straightforward to produce these sensors as point detectors, line sensors or image sensors, and they must have a performance close to the ideal detector limit. Point detectors should cost no more than €10, whilst line or image sensors should cost less than €100, including the cooling devices.

CMOS-based single-photon NIR image sensing

It has been demonstrated recently that novel types of CMOS-based image sensors are capable of detecting individual incident photons at room temperature. Accepting the need for cooling, it should also be physically possible to extend the cut-off wavelength from silicon's 1.1 µm to higher values in the NIR, while still being sensitive to each incident photon. This requires scientific progress in two domains. Firstly, novel CMOS-based charge detection circuits with sub-electron readout noise performance are needed. Secondly, it will be necessary to combine these charge detector circuits with semiconducting materials exhibiting a cut-off wavelength above silicon's 1.1 µm. Promising candidates include nanostructured (black) silicon, inorganic narrow-bandgap crystalline semiconductors (such as InGaAs), or novel types of organic semiconductors sensitive in the NIR spectral domain.

The primary goal is to employ CMOS technology for the integration of 2D arrays of charge detectors offering sub-electron readout noise, with suitable inorganic/organic material systems, and resulting in affordable single-photon resolution image sensors covering a large part of the NIR spectral range. Such CMOS-based single-photon NIR image sensors with one Megapixel should cost less than €100.

Low-cost, high-performance micro-coolers

A miniature refrigeration device is an indispensable element for any stable EIR light source and low-noise detector. Many physical methods are known for transporting heat, involving mechanical, magnetic, electrical, acoustic, incoherent/coherent radiation or thermal energy. In photonics, the predominant refrigeration device is the thermo-electric cooler (TEC), based almost exclusively on bismuth-telluride. Today's TECs are highly inefficient, typically exhibiting only 5–8% of the Carnot efficiency, compared to the 40–50% of a vapour-compressor. Novel solid-state concepts, such as the thermionic converter, can potentially go beyond 50% efficiency, and they can be manufactured with well-established microelectronics fabrication technology; their production can be very cost-effective and high levels of integration with other photonic elements can be achieved.

The primary goal is to develop affordable, miniature TEC devices capable of removing waste heat between 0.1 W (for EIR detectors) and 10 W (for EIR light sources), with an efficiency of close to 50% of the Carnot value, and at prices below €10 (0.1 W) or below €100 (10 W).

Passive optical devices

Development of optical instruments in the UV/VIS/NIR spectral domain is aided significantly by the availability of many passive optical elements such as lenses, mirrors, beam-splitters and gratings. For large volumes, manufacturers in Asia provide such elements with unit prices well below €1. The materials and technologies used for corresponding devices in the MIR spectral range are much more expensive. Therefore, optical designers are significantly limited in their design optimisation, and the prices of the resulting system are increased correspondingly. Hence a large demand exists for a complete set of cost-effective passive optical devices for the MIR spectral range, produced with affordable materials, and making use of Europe's advanced precision manufacturing technologies.

The goal here is to develop high-precision yet low-cost fabrication and coating technologies for the production of the passive optical elements, suitable for the efficient design of optical instruments working in the EIR spectral domain. The long-term aim is to provide large volumes of such components for prices around €1 per element.

Optical fibre light-guides and sensors

Low-loss optical fibres are ideal devices for the efficient guided transportation of NIR/MIR light, for accurate and minimally invasive probing, for the construction of NIR/MIR laser sources, as well as for the realisation of complete distributed fibre sensors. In addition, functionalised optical fibres can be very sensitive as chemical, biological or medical sensor systems, and the use of the NIR/MIR spectral range offers additional benefits for the performance of such cost-effective, simple-to-use biosensor systems.

The goal here is to develop a range of novel optical fibre sensors for distributed low-cost sensing in safety and security applications with enhanced sensitivity and functionality, and making use of advances in microstructured fibres, optofluidics and nanotechnology.

Measurement techniques for processes and production lines

Industrial exploitation of multi-band photonic sensing requires the development of comprehensive measurement techniques, making use of the advantageous properties of new photonic components.

This is an indispensable step for bringing inexpensive, multi-spectral/hyper-spectral measurement systems into production lines. To this end, account must be taken of the specific spectral and sensing properties of the new sources, sensors and other optical components in the EIR. While most of today's measurement techniques rely on visible light and silicon sensors, the great challenge is to develop a new generation of measurement systems fully exploiting the combination of spatial information with multi-spectral data.

Complete integrated photonic microsystems

Photonics has profited enormously from the adoption of planar fabrication and integration techniques developed for micro- and nanotechnology. Precise concurrent production of a number of photonic components in one fabrication step (for example using injection moulding or other low-cost replication techniques) results in products that do not require costly post-production alignment procedures, and thus achieves much lower fabrication costs. However, optical instruments working in the MIR spectral domain are still so expensive that it is not yet necessary to adopt the established integration techniques known from the visible spectral range. Since the mechanical tolerances are more relaxed in the MIR spectral range than in the visible, advanced low-cost additive manufacturing techniques might be employed, offering novel opportunities for the European manufacturers of integrated photonic microsystems.

The goal is to develop precise yet low-cost fabrication methods for the production of small and large quantities of complete, readily aligned photonic microsystems operating in the EIR spectral range.

Comprehensive photonic solutions for high-impact applications

The ultimate goal of any research action within the framework of *Horizon 2020* must be an innovative response to highly relevant socio-economic challenges. For the present case, this implies that

Photonics technologies are used to provide airport security. © Fotolia

complete multi-band photonic sensing solutions must be developed, providing for a safer and more secure society, through full utilisation of the as yet largely unexploited potential of the EIR spectral range. For this reason, there are two important problem domains that must not be neglected:

1. The main applications addressed are in the area of food/air/water/environmental safety and security, requiring affordable, simple yet reliable examination of gaseous, liquid and solid samples. Therefore, sample preparation is an important part in the development of comprehensive photonic solutions. If the concentration of the sought analytes is too low, it must be increased, for example through chromatographic methods, so that the optical measurement process generates sufficient signal. Hence, the development of accompanying consumables such as microfluidic, gas diffusion, and convection and optofluidic cells must be an integral part of the overall system development.

2. A central part of most EIR fingerprint measurements is the comparison of measured spectral data with the contents of a reference library. Much care and effort must be devoted to ensuring the availability of such a library, either through direct measurements or from compilations of available resources. This can then be used to provide a stable, efficient and dependable algorithms for the reliable determination of the constituents and their concentration in an analysed sample.

Expected impact for Europe

Europe could become the world leader in non-contact fingerprint diagnostics by commercially exploiting the as yet under utilised domain of multi-band UV/VIS/EIR photonic sensing for a safer and more secure society. Many of the scientific and technological capabilities to exploit the EIR spectral domain are already located in Europe. These include novel materials related to microelectronics, active/passive device fabrication, packaging of photonic components, development and production of photonic sub-systems, as well as development and deployment of comprehensive system solutions.

The envisaged EIR measurement techniques are not a replacement for high-sensitivity biochemical assay-based measurement systems, but instead provide a complement, bringing affordable, label-free fingerprint analysis methods from the laboratory into the hands of the consumer. In practice, these techniques will find much wider use than merely in the applications described above:

Analysis methods will be used for checking raw foodstuff materials, in-line controlling of manufacturing processes, and for confirming the safe sealing of packaged goods.

Food: EIR analysis methods will be used for checking raw foodstuff materials, in-line controlling of manufacturing processes, confirming the safe sealing of packaged goods, and for assuring the quality of processed food. The non-contact nature of photonics enables such checks without pre-processing food samples, even without opening the package. EIR analysis methods will also enable retailers and customers to judge the ripeness of fruit and vegetables, and to determine whether food is still safe to eat. This could help to reduce significantly the percentage of discarded food, which, according to a recent UN report, currently amounts to about 30% of all produced food[13]. The global market for processed food is more than €2.6 trillion, and for food processing machinery and equipment it is approximately €35 billion[14].

Environment: Contamination of our environment, be it fresh water resources, seawater, soil, or the air we breathe, is an increasing worry for our industrialised society. By allowing the screening of large volumes of air, water and soil probes, EIR analysis methods provide an excellent complement to the more specific and highly sensitive biochemical analysis techniques. An important application is the detection and prevention of oil contamination in seawater, for example, through the routine water inspection in ship ballast tanks. The global market for environmental monitoring is about €10 billion[15].

Water: Drinking water and treated wastewater alike must fulfill certain purity requirements. EIR measurements will be a valuable complement to existing biochemical analysis techniques in screening large volumes of water for contaminations in moderate concentrations. The global market for water analysis instrumentation is about €1.5 billion[16].

Efficient combustion: Many of our sources of electricity, heat and light are based on combustion processes. Frequently, the employed fossil or renewable fuel is not of constant quality, and the combustion process has to be adapted for varying fuel quality. It would be of great value to know the composition of the fuel used, be it in domestic heating systems or in public buildings, in moving vehicles or especially in ships. The same is true for the analysis of the exhaust gases. In-line measuring

13 J. Gustavsson et al., *Global Food Losses and Food Waste*, Food and Agriculture Organization (FAO) of the United Nations, Rome, 2011

14 *Food Processing Machinery and Equipment – A Global Strategic Business Report*, Global Industry Analysts Inc., San Jose (USA), May 2012

15 *Environmental Sensing and Monitoring Technologies: Global Markets*, BCC Research, Wellesley (USA), October 2011

16 *Water Analysis Instrumentation: A Global Strategic Business Report*, Global Industry Analysts Inc., San Jose (USA), August 2011

Roadmap for 2014–2020

	2014/2015	2016/2017	2018/2019	2020
Critical path from science to market	1. Demonstration of EIR system concepts with high application potential. 2. Invention of new potent low-cost EIR components.	1. Field tests with demonstrator systems. 2. Realisation of new EIR component prototypes.	1. Design and realisation of low-cost versions of successful systems using new EIR components. 2. Ramp-up of EIR component and sub-system production.	International market penetration with new low-cost EIR systems, components and applications.
Technological challenges	New materials and principles for EIR lasers, LEDs, 1D/2D detectors, TEC and passive optical devices.	Optimisation of device architecture and performance. Simplification of device fabrication processes.	Buildup of cost-effective production capacity using modified micro/nano-electronics fabrication facilities.	Sustainable performance and reliability at constantly falling prices of systems and components.
Research actions	Exploration of novel concepts in EIR light emission, detection and metrology with high application potential and low cost.	Characterisation and optimisation of device structures and performance. Drive towards compatibility with micro-electronics production facilities.	Optimisation of system performance. Identification of novel application fields. Further simplification and miniaturisation of EIR systems.	Data collection in field tests; validation and optimisation of concepts; buildup of databases and practical experience.
Innovation requirements	Buildup of European network of competence in EIR devices and systems. Involvement of existing producers of photonic materials and components in Europe. Search for secondary applications of EIR spectral range with high value.	Establishment of supply chains for advanced EIR optoelectronic components and metrology systems with emphasis on European suppliers of high-margin production steps. Support of European startups in the EIR domain, created as a result of novel concepts found in the first phase of the program.	Involvement of end users in primary and secondary application fields: Food/ air/water/ environmental safety and security; medical diagnostics/recycling/ combustion & building control/surveillance & public place security/ anti-counterfeiting. Demonstration actions for all selected showcase examples.	Joint field tests with end users. Buildup of user communities, producing and exchanging databases and practical experiences. Support of system design and application startups created as a result of the previous demonstration successes.
Cross-cutting Key Enabling Technologies (KET) issues	Involvement of KETs relevant for material and device fabrication: Advanced materials, micro nano-electronics and advanced manufacturing.	Joint selection of high impact application areas in safety & security of food, air, water & environmental control, in close collaboration with other KETs and ETPs. Elaboration of secondary applications as discussed below (medical, waste treatment, building control, anti-counterfeiting, traffic safety, industrial metrology, etc.).	Buildup of user groups and European competence network in EIR system design and applications. Collaboration with other KETs and ETPs in the elaboration of system specifications and conditions for practical applications of the developed concepts, devices and sub-systems in other domains.	Promotion of the EIR spectral range for applications beyond those demonstrated in the program. Identification of applications with highest socioeconomic values created in Europe.

of the produced levels of O_2, COx and NOx makes it possible to optimise the combustion process, increasing efficiency, whilst producing the minimum volume of harmful gases. In all these applications, it has already been proven that EIR measurements can provide viable solutions, but monitoring system prices must be reduced by 1–2 orders of magnitude before EIR fuel quality checks and exhaust gas analysis can become economically viable.

Building control: Stricter building codes for environmentally friendly houses involve greater insulation of buildings, to such a degree that internal air quality is increasingly becoming an issue. In particular, levels of CO_2 and some volatile organic compounds causing unpleasant odors must be controlled to optimise ventilation. The high prices of existing EIR analysis systems imply that such solutions will only be applied to large public buildings. Price reduction would make it possible to provide every low-energy house with this much-needed capability.

Recycling and waste treatment: The sorting of wastepaper, cardboard, plastics/polymers, fuels, industrial waste, etc. for recycling or proper disposal can be done at high speed using NIR/MIR analysis systems. The current high cost means that only larger facilities have such sorting systems. Lower prices of these analysis devices will allow much broader utilisation of automatic sorting systems. Also, networks of local automatic plastics recognition and tracking systems can be realised for plastic waste in rivers, lakes and seas, thus reducing the environmental contamination of plastic trash. The total world waste market (from collection to recycling) is about €300 billion [17].

Photonic solutions contribute to a sustainable recycling and waste management. © Fotolia

Optical metrology: Optical 3D measuring systems are essential components for high-precision fabrication, as safety measures in automatic doors and robotic workstations, in private and public transportation, as well as in novel user interfaces for computers and games. The precision of these metrology systems could be substantially increased and their ubiquitous outdoor use would be made possible if the interference of background radiation (sunlight) were reduced. According to the European eye safety norm EN 60825, the maximum permissible exposure in eye-safe metrology systems may be increased by more than 100,000 times by shifting the wavelength of the active light source to the range of 1.5–1.8 µm, beyond the reach of silicon [18]. The global optical metrology market is about €20 billion.

Medical diagnostics: Novel approaches to non-invasive medical diagnostics include breath analysis, and it has been conclusively shown that a number of relevant diseases, in particular cancer and diabetes, can be detected by analysing the patient's breath for the presence of specific combinations of biomarker gases. Such measurements can be done using non-invasive optical techniques alone, operating in the MIR spectral range. Providing that prices of such breath analysers drop substantially,

17 P. Chalmin and C. Gaillochet, *From Waste to Resource – An Abstract of World Waste Survey 2009*, Edition Economica, Paris (F), 2009

18 IEC/EN 60825–1 , *Safety of Laser Products, Part 1: Equipment Classification, Requirements and Users Guide*, International Electrotechnic Commission Geneva (Switzerland), 2007

it is conceivable that each general practitioner practice could be supplied with such an instrument for rapid, low-cost and early screening, as well as monitoring the progress of therapeutic regimens. The global in-vitro diagnostics market is €45 billion [19].

Secure society: Enhanced protection of travelers at airports and train stations, or visitors in public spaces is a major application area. For example, the detection of explosives through 'fingerprint' gas analysis, improved recognition of individuals through EIR signatures (distribution of veins in face and hands), more effective identification of prohibited or dangerous goods through effective large-scale cargo screening, and improved surveillance in public spaces by identification of suspicious persons or luggage items with unusual MIR profiles. The worldwide security equipment market is €76 billion [20].

Safer traffic: The presence of pedestrians or animals in the road is straightforward to detect through the infrared radiation emitted by warm bodies, so MIR enabled night-vision offers significant safety enhancements for night driving. Optical time-of-flight 3D imaging for reliable daytime use in automotive vehicles requires the use of the higher illumination powers that are possible in the NIR spectral range (as discussed above). Finally, rapid low-cost checks for drivers possibly under the influence of drugs or intoxicating beverages are readily performed in the NIR/MIR spectral range, without the use of any consumables. More than 60 million cars are produced worldwide every year, all of which could benefit from the added safety offered by these IR-enabled sensing devices [21].

19 *Strategic Analysis of the Global In Vitro Diagnostic Market*, Frost & Sullivan, San Antonio (USA), July 2010

20 *World Security Equipment to 2014 – Demand and Sales Forecasts, Market Share, Market Size, Market Leaders*, The Freedonia Group, Cleveland (USA), December 2010

21 OICA Correspondents Survey: *World Motor Vehicle Production 2011*, International Organization of Motor Vehicle Manufacturers, Paris (F), 2011

CCTV systems employing photonics technologies ensure increased security in public spaces. © Fotolia

Anti-counterfeiting: Counterfeiting accounts for 5–7% of world trade every year, corresponding to almost €500 billion [22]. When health-related products, such as pharmaceutical drugs, food or beverages are counterfeited, the indirect safety costs of counterfeiting exceed the already enormous economic damage. The NIR/MIR spectral range offers novel approaches and low-cost verification means to label products in all industrial branches, including personal identification items, such as passports or identity cards, as well as banknotes, credit cards, etc..

Non-destructive testing: Safe construction of mechanically challenging structures requires reliable, non-destructive testing (NDT) of the employed materials and components. In particular, the demand for stronger and lighter weight parts leads to a replacement of metallic elements with composite materials, such as carbon fibres, glass fibres and composite honeycombs. As an example, a new Boeing 782 Dreamliner consists of 50% (by weight) of such composite materials. Conventional NDT techniques (e.g. X-ray, ultrasonic, eddy current inspection) need to be complemented with novel inspection techniques tailored for these composite materials. The FIR spectral range offers unique advantages for the detection of surface and subsurface damage, such as delamination, impact micro-fractures, porosity, etc..

22 *ACG Statistics on Counterfeiting and Piracy*, The Anti-Counterfeiting Group, High Wycombe (UK), 2010

A major application area will be providing enhanced protection to travellers at airports and train stations, or citizens in public spaces.

2.6 Design and Manufacturing of Optical Components and Systems

Main socio-economic challenges addressed

As a fundamental pillar of modern industry, a Key Enabling Technology, photonics underpins solutions for the widest possible range of socio-economic needs. For example, the Internet of today depends on the ubiquitous application of photonics in telecommunications infrastructure and, as our society become ever more information-intensive, our needs in this respect will continue to grow. Laser-based techniques have revolutionised manufacturing industry and medical procedures, whilst photonic sensors are indispensable in providing a safer environment.

These examples serve only to illustrate the wider fact that photonics is pervasive in modern life. Whilst specific applications are addressed in the previous chapters contributed by Work Groups 1–5, there are numerous aspects that are generic to a wide range of applications: these are the enablers of our field and accordingly deserve focused attention in their own right. We accordingly emphasise here the development of technologies that have the potential to transform major sectors of our industry.

It is vital that European industry is strong at every level, from devices and components through to systems, also embracing manufacturing equipment and methodologies.

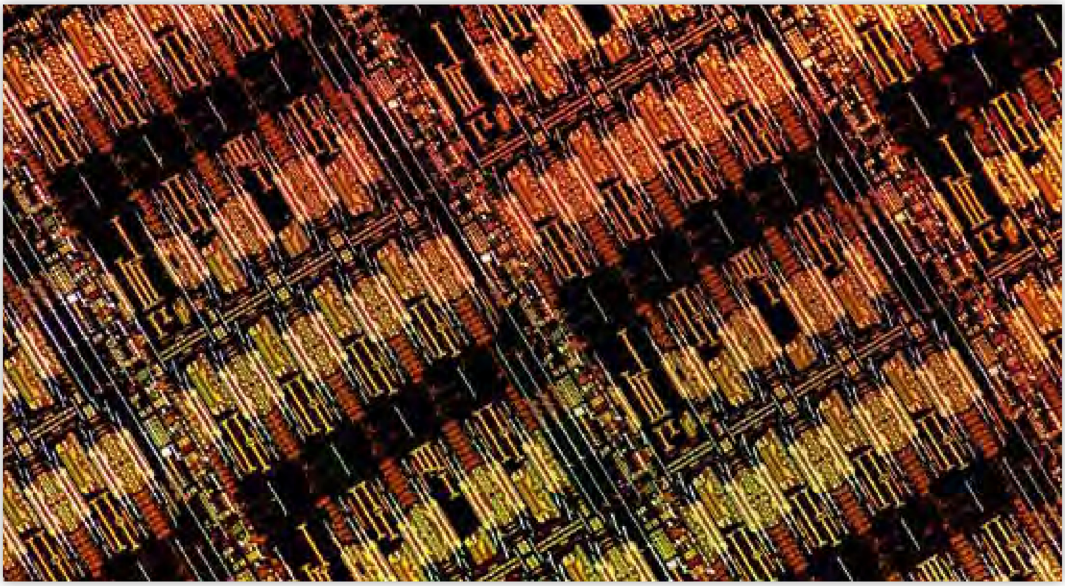
In order to maximise the benefit to European society, it is vital that European industry is strong at every level, from devices and components through to systems, also embracing manufacturing equipment and methodologies.

Major photonics needs

As has been noted throughout this document, photonic technology is a critical enabler for an extremely broad range of industrial products and services, as well as a vital tool for scientific research across many disciplines. Although the economic impact may be most apparent at the higher levels of the food chain, for example in equipment and services (such as telecommunications, health care and manufacturing using laser tools), experience tells us that competitiveness here is vitally dependent upon access to the most advanced photonics technologies at the component level. Without differentiating technology, truly innovative products will surely be elusive, and, without strong support for discovery and innovation, we cannot achieve strong added-value production. We therefore emphasise the importance of a European supply chain in the strategically important areas of component and systems technology, embracing high-volume manufacturing as well as high-value, specialised components.

In the following text we set out a top-level agenda based on a number of key technical capabilities, including photonic integrated circuit (PIC) integration platforms, advanced semiconductor device technology, electro-optical circuit board technology, new materials, and new technologies such as nanophotonics, which constitute a prerequisite for Europe's continued ability to innovate in photonics and to be competitive in manufacturing. These capabilities represent key enablers for a vibrant European components and systems industry, able to thrive in global markets and to deliver the socio-economic benefits for Europe.

In addition to stimulating the development of new photonic technologies, it is vital that our programme facilitates the availability of, and access to, these technologies by innovators and entrepreneurs across the EU. We have accordingly identified a number of measures that are designed to ensure that new technology is brought to the marketplace in the most timely manner, managing the risk factors that might prove insuperable for any individual player. Our recommendations include pilot manufacturing capabilities in key constituent technologies, including photonic integrated circuits, integration of photonics with electronics, certain classes of semiconductor devices and



A wafer of 100Gbit/s InP modulator PICs © Oclaro

high-functionality, photonic-enabled electronic systems. In this way, technologies requiring high initial investment may be brought to the point where entrepreneurs can ascertain their true value and take forward the task of building viable and vibrant businesses on established foundations, without taking commercially unacceptable risks.

Involvement of value chain partners

Our vision is of a European industry that is strong at every level, from devices and components through to systems, also embracing manufacturing equipment and methodologies. Accordingly, all members of the value chain need to be fully engaged, from fundamental research in materials through to the users of the systems, in which photonic technologies are deployed.

We perceive major opportunities to build and sustain a vibrant manufacturing industry in Europe based on advanced technology, best-in-class design and innovative manufacturing techniques. In order to achieve this objective, Europe needs to grow and support a photonic eco-system having the critical mass of skills and capabilities, an environment in which photonics and its client industries can advance together. *Horizon 2020* provides an important opportunity to develop new design tools and processes, as well as enabling technologies, manufacturing tools and techniques, which will help to ensure that Europe has these skills and capabilities in place. Furthermore it must underpin the education and training of a new generation of technically skilled and innovative people, who can carry out the research, innovation and entrepreneurial activity needed to maintain the forward momentum of our programme.

The fragmentation of European research infrastructure has long been identified as a limiting factor, and the Network of Excellence initiative in Framework 6 was a first attempt to put this right. Certainly the aim of establishing larger virtual research teams and pan-European facilities, thereby absorbing capital cost as well as providing an intellectually stimulating environment, should be a factor in our future policy. It will be necessary to work with existing research and innovation centres to ensure the most efficient coordination of activities and maximum leverage on future investment.

We need to engage all stakeholders in the coordination of these efforts. As noted elsewhere, this will require discussion and partnership with other industries, including microelectronics, life sciences, ICT and advanced manufacturing. Furthermore, it is vital that we engage and support the full spectrum of industrial players, from SMEs to large manufacturing enterprises.

Major photonic research & innovation challenges

Our vision is built on the foundations of world-leading research in focused areas that are relevant to photonics across the board, coupled with initiatives designed to ensure that the resulting technology is put to use in the most efficient and effective manner. We have identified a number of priority areas for investment in generic technologies that will have a high impact across a wide range of applications, thereby complementing the recommendations of the applications-oriented working groups. These relate specifically to the following areas:

- Photonic integration, including the development of generic integration platforms and foundry models, thereby allowing complex linear and nonlinear photonic functionality to be realized in an integrated form
- Integration of photonics with microelectronics at the chip, board and system levels
- Technologies for cost-effective manufacturing of components and subsystems, including automated photonic device assembly and electro-optical circuit board technology
- Semiconductor optical device technology, with particular reference to semiconductor lasers
- Exploitation of new materials, including new semiconductors and nanophotonic materials (for example, metamaterials & plasmonics), multi-functional fibres, and their associated fabrication technologies

Europe has taken the lead in developing integration technology platforms supported by generic foundry manufacturing, significantly increasing the effectiveness and applicability of Photonic Integrated Circuit technology.

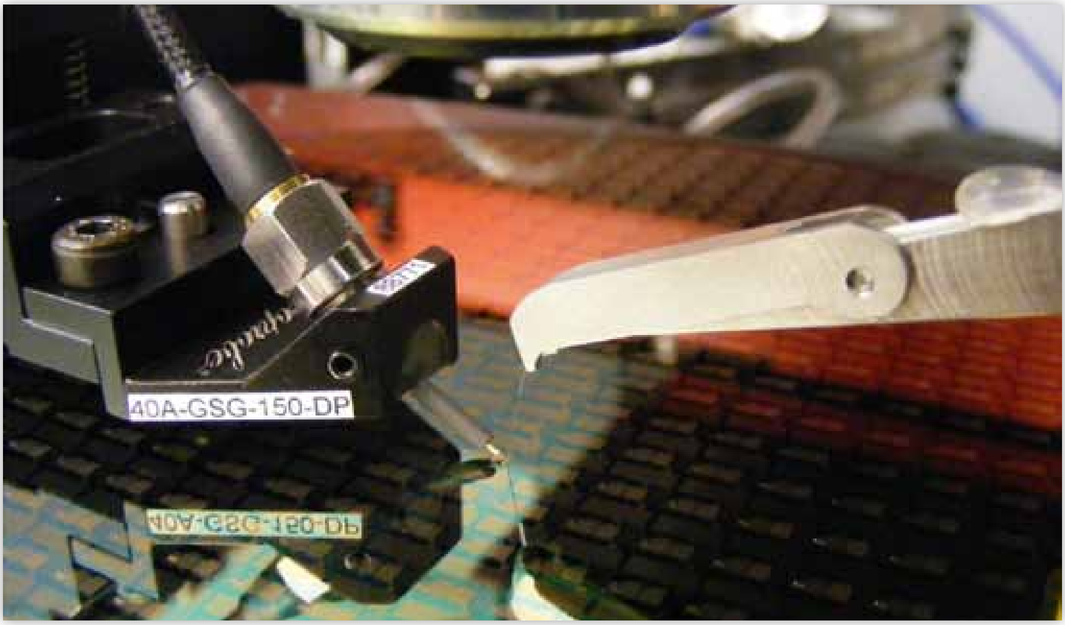
Our first recommendation relates to photonic integration. As in microelectronics, many applications can be addressed in a much more compact and cost-effective way by integrating the required functionality in a single chip of III-V semiconductor material (for example, indium phosphide, gallium arsenide), silicon, or dielectric material. As a result of past EU investments, Europe has a very strong position in these technologies. Whilst photonic integration is one of the most important keys to competitive advantage, present ways of working do not unlock its full potential. Not every supplier can be vertically integrated, and access to technologies by smaller companies, for example, SMEs, is currently very limited. Furthermore the large variety of photonic devices and technologies that have been developed is beginning to limit progress in the industry. Europe has taken the lead in developing a new way of working, based on integration technology platforms supported by generic foundry manufacturing, which can provide a step-change in the effectiveness and applicability of Photonic Integrated Circuit (PIC) technology. European initiatives on generic photonic integration have attracted great interest and are beginning to be emulated worldwide, particularly in the USA. It is vital that these initiatives are carried forward in *Horizon 2020*, so that the most advanced PIC technologies are developed in the most efficient way and made accessible for exploitation to the widest spectrum of end-users. Innovation actions in this area have been specifically identified as a priority by the applications-oriented work groups, especially in Information and Communications technology (Work Group 1).

The generic integration approach has proved highly successful in the microelectronics industry and although the challenges in applying the same methodology to photonics are different and are in some ways greater, we can nevertheless learn from the microelectronics experience. For instance, foundry-access programs, such as MOSIS in the USA, had a pivotal impact in the development of the VLSI industry, not least by training a large number of designers in circuit design techniques, and we therefore recommend that a similar approach should be adopted in Europe for application-specific photonic integrated circuits in silicon photonics, III-V semiconductors and dielectric and polymer materials. Furthermore, just as in microelectronics, we must invest significant scientific resources in the development and evolution of robust, accurate and efficient simulation and computer aided design (CAD) tools and in process and packaging technologies supporting the generic platform approach. Consideration should also be given to the integration of optical circuit design tools with systems-level simulation tools, in order to facilitate a holistic approach to the development of application-specific products based on PIC technology.

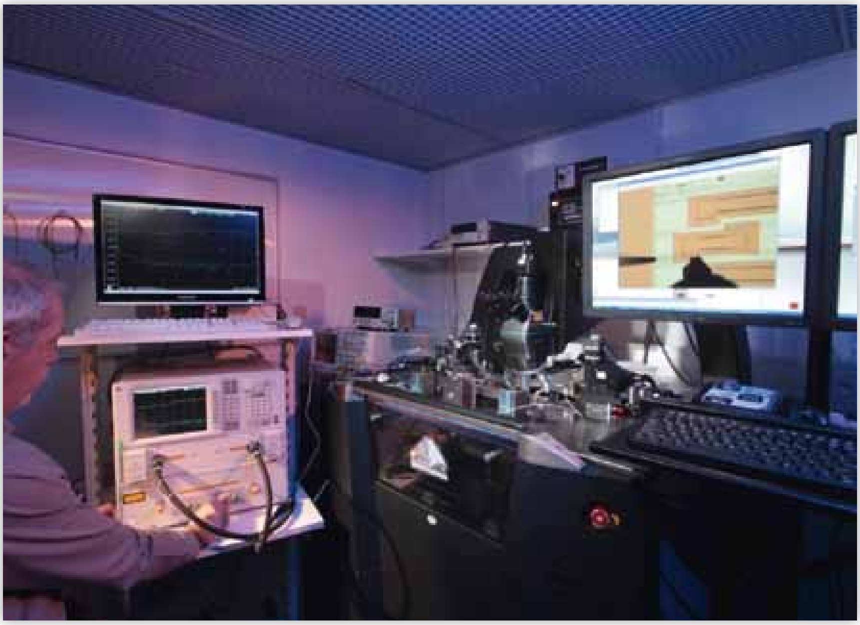
In order to expedite the future evolution of our chosen platforms, we propose research on large-scale integration processes allowing the seamless introduction of new technologies. It is vital that the platforms can embrace new technologies with potential for improvements in functionality, compactness, energy efficiency, manufacturability or cost-effectiveness. Technologies such as photonic circuits based on membranes, nanowires, photonic crystals, metamaterials and plasmonics, including optical antenna structures, should be supported, and opportunities sought to integrate these elements into generic PIC capabilities at the earliest opportunity. In addition, extension to new wavelength ranges (for example, visible, UV) should be addressed. Further advances in manufacturing techniques will certainly also be required, for example, developments in high-volume, high precision, and cost-effective techniques, such as nanoimprint lithography (NIL).

Alongside the development of device and circuit technology, a concerted attack must be made on the challenges of cost-effective manufacturing of components and subsystems. Here we need to deploy European expertise on robotics, automated precision assembly and test technologies to offset the cost advantage of Far-Eastern manufacturers, and ensure that the full value chain can be addressed within Europe. We envisage here a synergistic exploitation of electronic, optical and mechanical technologies in an optimum combination. New structures with improved capacity for heat dissipation and thermal control are essential, as are strategies for managing electromagnetic design challenges. European strengths in hybrid photonic integration, including photonic lightwave circuit technologies, should be exploited, along

European strengths in hybrid photonic integration, including photonic lightwave circuit technologies, are a major advantage.



High frequency wafer level testing of germanium photodiodes on silicon. © CEA-Leti



Wafer-level probe testing on 200/300 mm silicon wafers. © CEA-Leti

Photonics will provide the next level of performance for ICs, providing data links across individual chips, as well as optical interconnects between devices within a subsystem.

with developments in new optical elements, such as stacked micro-optics technologies and free-form optical surfaces. The emergence of laser-assisted manufacturing processes and of printing technology for additive deposition of functional materials offers further potential for enhancing competitiveness.

Major opportunities will result from a close coupling of advanced photonics with current trends in microelectronics. For example, we are already seeing the application of powerful digital signal processing in link equalisation for high-speed telecommunications systems (40Gbit/s, 100Gbit/s), as well as in data communications over shorter links. This approach is revolutionising the design of such systems and allowing photonics to reach new levels of performance and cost-effectiveness. Close integration of photonics with electronics is also of major importance for micro-opto-electro-mechanical systems (MOEMS), sensors and medical devices. It is vital that we accept and embrace the importance of electronics in photonic systems, and work to integrate the photonic and electronic parts very closely in our research and development strategy.

We note that IC manufacturers and processor architects are increasingly looking to photonics to provide the next level of performance in their devices, for instance in providing data links across individual chips, as well as optical interconnects between devices within a given subsystem. Besides improved functional performance, such approaches can also lead to significant improvements in power efficiency. The merging of electronic and photonic technologies at the circuit level will accordingly be a vital area of research. We anticipate that hybrid and heterogeneous integration techniques (for example, 3-dimensional multi-chip modules, III-V layers on active silicon ICs, dielectric/semiconductor hybrids) will augment the capabilities of photonics based purely on silicon. These advances must be supported by appropriate efforts on device packaging, as well as a holistic approach to integrated systems design.

At the level of building electronic systems incorporating photonic signal distribution and processing, new system integration approaches and manufacturing techniques are required in order to achieve maximum gearing from the photonic infrastructure. We note here electro-optical circuit board (ECOPB) techniques and advanced module concepts, such as will be required for next-generation processors, communications and information storage systems. Over the past decade, European research institutes and companies have spearheaded research and development in the field of circuit board embedded optical link solutions employing planar optical waveguides in polymer or glass. Europe must leverage its currently unparalleled expertise in this field towards the development of commercially viable processes for the manufacture of electro-optical circuit boards and modules, thereby securing a global competitive advantage. ECOB technology forms a vital part of the photonic eco-system of tiered optical interconnect solutions outlined in this roadmap. European manufacturers have built up an enviable position in global markets for semiconductor lasers, ranging from high power GaAs devices for laser-assisted manufacturing, printing and medical uses, to highly compact vertical cavity surface emitting lasers (VCSELs), such as are employed in human interface devices (mouse sensors, tracking devices), data links, data storage and biomedical/sensor applications. We must ensure that this European lead in III-V semiconductor device technology is maintained and strengthened. Research is required not only on the devices themselves, but also with respect to integration with modulators, MEMS devices and electronics, as well as incorporation into the complete electro-optical subsystems. Specific drivers that should be addressed include active imaging (including gesture recognition for human/machine interface and devices for automobile safety), as well as heat-assisted magnetic recording.

Whilst specific aspects of laser and optical system development are covered in the applications-led work packages, we note here the importance of continued improvements in power scaling, efficiency and extension to new wavelengths, including the ultra-violet, green, mid-infrared (>1.5µm) and THz spectral regions, all of which require corresponding developments in materials (semiconductors, glass and crystals), device and manufacturing technology, as well as advances in related optical components. These advances, in discrete as well as integrated form will underpin important applications in industrial manufacturing, printing, medical systems, visualisation, 3D-recognition, and in sensing and spectroscopy for biomedical and security applications, through exploitation of both linear and nonlinear interactions. We note also the need for continuing development in electro-optic transducers, modulators and detectors towards higher speeds and linearity, such as will be needed for Tbit/s interconnects, communications and sensor systems involving synergistic digital processing.

Finally, at the most fundamental level, we recommend a continuing focus on emerging technologies based on new materials, semiconductors, metamaterials, nanostructures and plasmonics, as well as multifunctional optical fibres. A large proportion of the most important advances in photonics have been related to the availability of new materials. Nanophotonic materials and structures, as well as heterogeneous combinations of materials (for example, III-V/Si), can provide the basis for unique capabilities, permitting photonic functions with unprecedented performance in terms of size, speed, power dissipation and functionality. Nanofabrication techniques with unique capabilities should be explored, including site-controlled epitaxy and epitaxy on patterned substrates. The potential of organic materials and organic-inorganic combinations should be fully investigated: whilst the role of these materials in OLED devices is discussed in Work Group 4, we envisage here a wider, generic applicability. Nanostructured surfaces can have chemically and biologically active functionality, which will facilitate the development of new sensor devices. Combination of existing and new materials with different functions (i.e. photon generation and saturable absorption) in a single optical fibre or waveguide will push forward the integration of functionalities presently performed by discrete components. Furthermore, these advances must be brought rapidly into use. Europe is performing well in many highly dynamic market areas that demand rapid innovation and the exploitation of disruptive materials and processes. This trend can be supported through coordinated research and the evolution of innovative manufacturing models. To summarise, a lead in the application of new materials and nanostructures in practical devices will underpin significant competitive advantage for European industry.

A lead in the application of new materials and nanostructures in practical devices will underpin significant competitive advantage for European industry.

We emphasise that in order to exploit the advances in research and development in the areas noted above, concerted actions are required to bridge the gap between research and exploitation. In particular, we have identified several areas where pilot production capabilities will be indispensable

Photonics is a strong export industry: the European market of optical components and systems represents about 11% of the total European photonics production, while the European market share in the global market place approaches 50%.

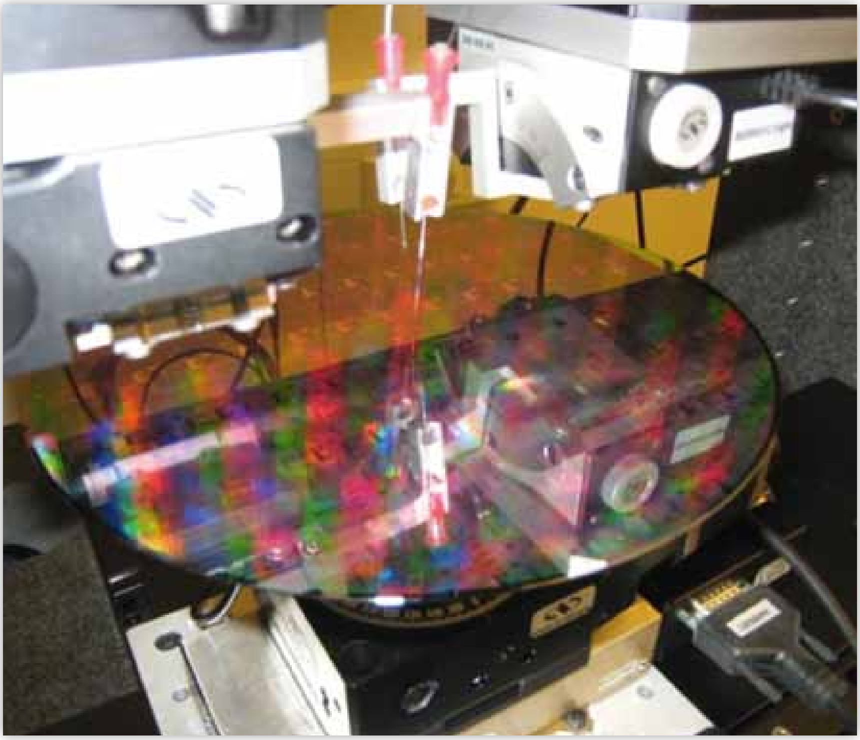
in proving technical capabilities at the appropriate scale, and bringing technologies within reach of entrepreneurial companies in the various application domains. These actions are identified specifically in the following roadmap timeline. This also identifies those areas where the required research, development and innovation actions should be coordinated between Photonics and other KETs, such as micro/ nanoelectronics, advanced manufacturing, materials and biotechnology.

Expected impact for Europe

As has been noted elsewhere, photonics is one of the most vibrant areas of the European economy. The total world market of optical components and systems was estimated in 2009 to be in the region of €15 billion with growth to more than €30 billion expected by 2015. Given their pivotal importance across a wide range of industries and services, from telecommunications and information systems to healthcare, investment in generic photonic technologies can have a disproportionately large impact. The leverage from advanced component technologies is extremely large: as an example, we may consider that the global market for telecommunications services, at more than €2 trillion, is critically dependent upon the capabilities of its constituent photonic elements. Similar considerations apply in other market sectors. The leading players in communications, laser technologies, lighting and bio-photonics all require innovative optical components as the basis for their differentiation in the marketplace. We should also note that photonics is a strong export industry: the European market of optical components and systems represents about 11% of the total European photonics production, while the European market share in the global market place approaches 50%. We note also that European manufacturers of production tools for photonics have a commanding position in world markets. In order to sustain this strong position against global competition, it is vital that momentum is maintained in the underpinning technology base.

The measures we propose will benefit small and large industries across Europe, as well as the public at large through the improved services that will be made possible with more advanced photonic technology. We recognise the importance of start-up businesses and SMEs in driving technical and product innovation, and several of the measures that we propose will be of particular benefit to SMEs. For example, the development of photonic integration platforms that can be made available widely through generic foundries should revolutionise access to high technology manufacturing for small companies across Europe.

Wafer-scale test of silicon photonic IC © Ghent University – imec



Roadmap for 2014 – 2020

We present here a roadmap addressing the following key technological challenges:

- Next-generation PIC technologies, especially generic technologies, maximising energy efficiency, density and functionality
- Innovative concepts for active photonics on silicon (including III-V/Si), embracing high-density, micron-scale emitters / modulators compatible with CMOS circuitry
- Ultra-high density photonic & photonic/electronic integration technology
- 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
- Next-generation assembly technologies facilitating high volume manufacturing of high precision discrete devices and PICs
- Technologies for electro-optic circuit boards and advanced module concepts, embracing organic/inorganic integration
- High power lasers, especially in relation to power scalability, beam quality, thermal management, robustness against environmental conditions
- High speed devices, including
  - Technology for data transfer at 1Tbit/s and beyond at chip level, with high linearity to facilitate analog operation, A-D conversion and digital signal processing
  - Energy efficient, scalable photonic switching & interconnect
- Sources for optical sensors and next generation storage systems (heat assisted magnetic recording)
  - Materials and structures for new wavelengths and wide tuning range (>100nm); integrated nonlinear devices to extend wavelength coverage; efficient plasmonic devices; precise beam delivery
  - Concepts for manufacturability for advanced devices (e.g. QCLs, active imaging devices, sources for HAMR), embracing subsystem integration (e.g. transmitter/receiver)
- New materials for photonics, including advanced semiconductor structures, ceramics, polymers, nonlinear crystals, metal-dielectric interfaces and multifunctional optical fibres/waveguides.
- New photonic coatings and functional surfaces, including applications of micro/nanostructuring and surface functionality for bio-applications, along with associated production strategies.
- The critical innovation-oriented challenge is to create infrastructure for open access to research and pilot manufacturing in critical technology areas, including photonic and electronic/photonic integrated circuits, packaging and assembly, key semiconductor technologies and advanced materials research.

Roadmap for 2014 – 2020

	2014/2015	2016/2017	2018/2019	2020
Research actions	**Photonic integrated circuit technology, availability, accessibility** ■ Develop processes & building blocks to-wards second generation of generic photonic integration platforms, with emphasis on maximis-ing energy efficiency, along with high density and increased functionality both at building block and at circuit level	**Photonic integrated circuit technology, availability, accessibility** ■ Technology for nano-photonic devices and circuits ■ Demonstrate viability of second-generation generic platforms through the proving of application-specific designs	**Photonic integrated circuit technology, availability, accessibility** ■ Emphasis on na-nophotonic devices, scalability to very high complexity circuits, maximum energy efficiency	**Photonic integrated circuit technology, availability, accessibility** ■ Proving of device technologies through candidate applications
	Electronic/photonic integration ■ See Cross-KET initiatives below	**Electronic/photonic integration** ■ See Cross-KET initiatives below	**Electronic/photonic integration** ■ See Cross-KET initiatives below	**Electronic/photonic integration** ■ See Cross-KET initiatives below
Note: RTD actions in assembly and packaging may be cross-KET with Advanced Manufacturing	**Assembly and Packaging** ■ New concepts for eco-nomic packaging and assembly of high per-formance, high func-tionality devices and PICs. Development of generic low-cost approaches in packag-ing, applicable to a broad range of PICs	**Assembly and Packaging** ■ Continuation of programme; establish technology base for innovation actions (see below)	*Research actions for the second part of the Framework will follow on from the research of the first four years, taking on board new developments in devices, assembly technologies and materials.*	
Note: RTD actions in electro-optic circuit boards and advanced modules may be cross-KET with Advanced Manufacturing	**Technologies for electro-optic circuit boards and advanced module concepts** ■ Concept research, fundamental technol-ogy development	**Technologies for electro-optic circuit boards and advanced module concepts** ■ Establish manufactur-ing technology and standards, leading to pilot line actions (see below)	*Research actions for the second part of the Framework will follow on from the research of the first four years, taking on board new developments in devices, assembly technologies and materials.*	

	2014/2015	2016/2017	2018/2019	2020
	Semiconductor Photonic Devices ■ High power lasers featuring high scalability, beam quality, thermal management, robustness against environmental conditions ■ Technology for 400Gbit/s-1Tbit/s on chip; high linearity; energy efficient, scalable photonic switching & interconnect ■ Source technology for active imaging, sensor and storage solutions (HAMR)	**Semiconductor Photonic Devices** ■ Continuation of 2014/5 programme	*Research actions for the second part of the Framework will follow on from the research of the first four years, taking on board new developments in devices, assembly technologies and materials.*	
	New materials and functionalities ■ Semiconductor and dielectric materials for enhanced functionality photonic devices, including micro/nanostructuring and plasmonics; multifunctional components (optical fibres and waveguides)	**New materials and functionalities** ■ Creation of shared infrastructure for research in advanced materials for photonics	*Research actions for the second part of the Framework will follow on from the research of the first four years, taking on board new developments in devices, assembly technologies and materials.*	
Innovation requirements	**Photonic integrated circuit technology, availability, accessibility** ■ Rollout of first-generation generic foundry platforms, building on existing capabilities with additional	**Photonic integrated circuit technology, availability, accessibility** ■ Support and develop pilot foundry production capabilities based on first-generation PIC technologies,	**Photonic integrated circuit technology, availability, accessibility** ■ Maintain support for 1st generation platform, including access for researchers and SMEs	**Photonic integrated circuit technology, availability, accessibility** ■ Continue to support and develop PIC platforms through an access programme for researchers and SMEs,

	2014/2015	2016/2017	2018/2019	2020
	targetted investments to establish pilot production facilities. ■ Qualification of first-generation platforms for demanding reliability requirements	with availability to researchers, SMEs and larger enterprises ■ Establish short turnaround time in multiple technologies (InP, Si, PLC) ■ Plan and invest in facilities to facilitate the introduction of second-generation integration platforms with enhanced capabilities including energy efficiency	■ Qualification of second-generation photonic integration platforms ■ Establish pilot manufacturing of second-generation PIC platforms with availability to researchers, SMEs and larger enterprises	following the successful example of MOSIS in VLSI
Note: Innovation actions in assembly and packaging may be cross-KET with Advanced Manufacturing *Note: Innovation actions in electro-optic circuit boards and advanced modules may be cross-KET with Advanced Manufacturing*	**Electronic/photonic integration platform** ■ See cross-KET activities below **Assembly and packaging** ■ Plan and prepare for pilot manufacturing facilities for discrete devices and PICs, including generic packaging approaches **Technologies for electro-optic circuit boards and advanced module concepts**	**Electronic/photonic integration platform** ■ See cross-KET activities below **Assembly and packaging** ■ Establish pilot for next-generation assembly of high volume, high precision discrete devices and PICs **Technologies for electro-optic circuit boards and advanced module concepts** ■ Plan pilot line implementation	**Electronic/photonic integration platform** ■ See cross-KET activities below **Assembly and packaging** ■ Initiate pilot line operations for high precision, high volume PIC and laser assembly **Technologies for electro-optic circuit boards and advanced module concepts** ■ Pilot line roll out 2018	**Electronic/photonic integration platform** ■ See cross-KET activities below **Assembly and packaging** ■ Continue and monitor pilot line operations **Technologies for electro-optic circuit boards and advanced module concepts** ■ Continue, monitor and facilitate pilot line operations

	2014/2015	2016/2017	2018/2019	2020
	Semiconductor Photonic Devices ■ Plan for qualification actions, standardisation, pilot line implementation in following period ■ Continue dialogue on management of semiconductor materials from product safety and manufacturing viewpoint, including the REACH initiative	**Semiconductor Photonic Devices** ■ Manufacturability and qualification for critical semiconductor power technologies (e.g. QCLs, active imaging, sources for HAMR) ■ Pilot line implementation for specific device technologies of critical European importance	**Semiconductor Photonic Devices** ■ Open and facilitate pilot line operations	**Semiconductor Photonic Devices** Continue, monitor and facilitate pilot line actions
Cross-cutting Key Enabling Technologies (KET) proposals	**Electronic/photonic integration (cross-KET with micro/nano-electronics) : RTD** ■ Develop innovative concepts for active photonics on active silicon ICs (including III-V/Si), with emphasis on high-density, micron-scale emitters/modulators, fully compatible with integration on CMOS electronic circuits	**Electronic/photonic integration (cross-KET with micro/nano-electronics): RTD** ■ Continued, with aim of establishing platform for generic use in the following period	**Electronic/photonic integration (cross-KET with micro/nano-electronics): RTD** ■ Whilst transferring capabilities into pilot production (innovation actions), initiate research into capability enhancements, including compatibility with forthcoming ITRS CMOS nodes	**Electronic/photonic integration (cross-KET with micro/nano-electronics): RTD** ■ Continuation of research action from 2018/19

	2014/2015	2016/2017	2018/2019	2020
	Electronic/photonic integration platform (cross-KET with micro/ nano-electronics): Innovation ■ Develop current concepts towards open access (performance, compatibility and usability goals	**Electronic/photonic integration platform (cross-KET with micro/ nano-electronics): Innovation** ■ Qualify first-generation electronic/ photonic platform; establish pilot manufacturing capabilities	**Electronic/photonic integration platform (cross-KET with micro/ nano-electronics): Innovation** ■ Release first generation electronic/ photonic platform to designers and SMEs through pilot manu-facturing lines ■ Qualify second-generation, high functionality, ultra-compact photonics on active CMOS; plan pilot production capabilities	**Electronic/photonic integration platform (cross-KET with micro/ nano-electronics): Innovation** ■ Introduce pilot lines for second-generation electronic/photonic platforms ■ Sustain access to platforms for researchers, SMEs and larger enterprises
Additional candidates for cross-KET programmes	**Cross-KET activities** ■ Device assembly and packaging tech-nologies, including pilot lines and related equipment (Advanced Manufacturing) ■ Electro-optic circuit boards and advanced module concepts (Advanced Manufacturing) ■ Materials and Nanostructuring for photonics (Advanced materials), including shared infrastructure ■ Structural adaptation and bio-active photonic devices (Biotech)	**Continued …** Detailed planning in collaboration with KET ETPs	**Continued …** Detailed planning in collaboration with KET ETPs	**Continued …** Detailed planning in collaboration with KET ETPs

2.7 Education, Training & Disruptive Research

Main socio-economic challenges addressed

Major progress is needed both on advanced research, and on education and training of highly-skilled workforce, if photonics is to address successfully the major socio-economical challenges facing Europe, ranging from health care to security, from energy saving to efficient and clean industrial production, and from environmental protection to fast and efficient communications.

Indeed, the industrialised world and developing countries alike have to address the problems of sustainability and quality of life, and these will require new approaches and solutions. Photonics, in recognition of its strategic significance and pervasiveness throughout many industrial sectors, has been identified as one of the Key Enabling Technologies for Europe. Not only does advanced photonics research offer new technical solutions for existing problems, but it also paves the way to as yet unimagined applications. The education and training of high-level professionals and a skilled workforce, including technicians, will allow innovation in photonics to be sustained, thus ensuring continued economic growth and employment.

Major photonics needs

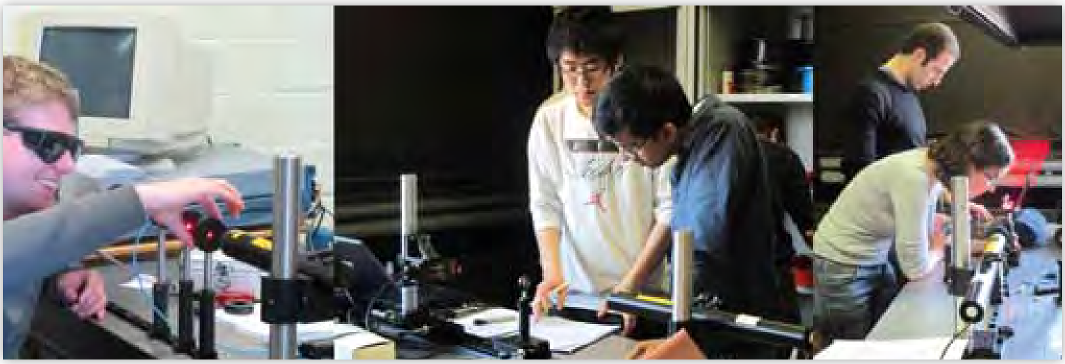
Three main photonics fields have been identified that must be addressed by advanced research to tackle the main societal challenges and produce innovative solutions across the sector:

- **Nanophotonics** (including graphene photonics, metamaterials, and plasmonics). These offer enormous improvements in sensing, imaging, and energy generation.
- **Quantum optics and quantum information.** This technology will revolutionise the field of computing, data processing and secure communications, but also has the potential to impact the field of sensing.
- **Extreme light** (including high power, extreme wavelengths and ultra-short pulses). This technology will broaden the application of light-matter interactions, thereby opening up innovative new techniques for sensing, imaging, material characterisation, material processing, and advanced manufacturing, and also playing a major role in fundamental studies.

Achieving these goals requires specific actions in education and training, aimed at addressing three specific target groups – young minds, professionals, and society at large. The main actions identified to address this are:

- outreach towards young minds, the general public and political authorities, aimed both at attracting more students, and at creating a strong consensus and awareness of the importance of photonics.

Education and training of high-level professionals and a skilled workforce, including technicians, will allow innovation in photonics to be sustained, thus ensuring continued economic growth and employment.



Hands-on training during a Photonics Laboratory course at VUB. © NA, VUB Brussels

- strengthening the cooperation with industry, both to better match their knowledge and skills needs in third and fourth-level education programs, and to offer life-long learning programs and vocational training.

Involvement of value chain partners

The inherent pervasiveness of photonics and its interdisciplinary nature require the broad involvement of many value chain partners, both as directly cooperating partners for RD&I, and as potential end-users. When dealing with advanced research, it is clear that interaction with all the other Key Enabling Technologies and related platforms will be essential, so as to exploit synergies and achieve higher levels of innovation. In terms of end-users, all industries developing photonic components and systems need end-users to be involved at the earliest stage, to ensure that research roadmaps address their specific needs in terms of properties and functionalities. Present and future societal needs should also be considered when defining medium and long term research goals.

The various value chain partners will each have a role in the education and training system actions:

- primary and high-school teachers need to be involved for effective outreach programs aimed at young students
- science and technology museums have to be targeted to set up exhibitions for the general public
- communication experts and scientific journalists need to participate in communication projects based on conventional and new media
- photonics 'users' will provide essential perspective for promoting interdisciplinary education, embracing photonics and its cross-fertilisation with other technologies for new applications
- the technical management and HR of photonics-based or photonics-enabled industries, together with both local and European political authorities, need to be involved in the definition of life-long learning and vocational training programs.
- regional and national clusters will support local smart specialisation strategies.

Major photonics research and innovation challenges

During the preparation of Photonic21's second strategic research agenda and the photonics vision paper, an extensive analysis has been performed to identify the areas of major potential impact on medium-long term societal challenges and on future European industrial competitiveness, thereby ensuring that advanced research can be defined effectively.

Building on this analysis, the major challenges for research, education and training were identified, and actions defined to be undertaken within *Horizon 2020*.

Research

Adopting a medium-long term perspective, advanced research must consider as the driving force of future innovation, pushing beyond the currently foreseen applications. A number of critical aspects should be considered:

- Working with industry to identify what new photonics properties and functionalities will be needed to improve present components and systems, that they do not yet know how to achieve. This can be used to construct targeted roadmaps, identifying directions and actions required to achieve specific goals. With many new fields being explored, a wide range of possible solutions must be studied to identify the optimal ones, with greatest potential for industrial applications with acceptable time to market.
- Ensuring that disruptive research is not overlooked. Many new photonics applications currently cannot be predicted, so there must be room for exploring the unexpected.
- An open innovation approach involving the close cooperation between universities, public research institutions and industries is becoming essential in our knowledge-based society, and

will promote greater European competitiveness through advanced research.

- The establishment of open-access distributed high-tech facilities, so as to allow advanced experiments to be performed, new materials to be developed and characterised, and devices and prototypes to be fabricated and tested in the most efficient way.

Details of the roadmap for research in the time frame of 2014-2020 are given in the following table. However, it is useful to identify a number of representative examples of the 'hot topics' – clearly valuable developments that as yet cannot be achieved with present technological capabilities, such as:

- Nanoscale imaging
- Low-loss semiconductor photonics
- Semiconductor/other material lasers with higher efficiency or for currently inaccessible wavelengths
- Non-reciprocal semiconductor materials
- New materials for THz
- Optical materials with optimal thermal characteristics
- Single photon sources and detectors operating at room temperature
- Bio-compatible material for artificial retina

Over a longer time-scale, further developments can be considered coming from fundamental science, and based on novel concepts and approaches for materials and processes. These could lead to useful applications, but as yet the specific application need or means of fully exploiting their potential are unknown. Examples falling within this category include:

- Photon-photon and photon-phonon interactions
- Light-matter interaction in 'extreme' conditions
- New materials (engineered materials, new organic materials)
- New aspects of photonics at the nanoscale
- Unexplored new material systems (graphene, silicene)

Innovative research should always be developed following guidelines based on its potential impact for making photonics more accessible, eco-friendly, low-cost, or in replacing or reducing use of dangerous or scarce materials.

Education and training

For education and training, one of the most critical challenges will be to overcome the present major difficulty facing the photonics community, namely of securing the necessary knowledgeable and skilled workforce. This shortage applies at all levels, from technical management and R&D positions through to technical staff, and is encountered both in industry and academia.

In the longer term, solving these shortages will require increasing the wider community interest in photonics, and an awareness of its importance.

Students experience the 'fascination of light'. © Catalunya Caixa

Students from the secondary school working with the photonics explorer in their class room. © VUB

A strong interaction with industry will be essential for establishing vocational training and life-long learning, particularly so for SMEs.

Details are given in the roadmap table, but it is worth highlighting some general aspects:

- coordinated actions will be needed to take full advantage of all possible activities and outreach projects, so as to maximise impact
- specific attention should be devoted to follow-up actions, and the most successful actions should be extended and supported until they can become self-sustainable
- the involvement of non-photonics players (communication experts, school teachers, etc.) will be essential to break down existing barriers within the photonics community
- successful ambassadors should be identified for promoting photonics in the wider community
- cooperation with local and national authorities will be needed to ensure sustainability. Industries and private partners should also be encouraged to support outreach programs
- future young students should be exposed at the earliest opportunity to fascinating programs in photonics (following the examples of Photonics Explorer and Luka's Land of Discovery)
- establishing awards for innovative students and competitions for teams of young researchers on specific problems
- showcasing photonics exhibitions in all major Science and Technology museums throughout Europe, including interactive experiments suitable for visits of students with their teachers
- ensuring that appropriate attention is devoted to demonstrating the present impact and future innovation potential of photonics, rather than merely presenting an historical perspective
- simpler but fascinating photonics installations provided at high throughput public environments (airports, train stations, commercial malls, etc.)
- photonics events (shows, conferences, dissemination activities) co-located with non-scientific activities (e.g. suitable art or photography exhibitions)
- full use of available mass media (TV, press, internet) for dissemination programs.

All actions should take care to address the gender problem that, despite continuous effort, still faces us with a clear gender unbalance in science and technology.

Clearly outreach is not the only challenge. A wider availability of photonics courses will be needed at the university level, and these must be matched with the development of entrepreneurial skills. A strong interaction with industry will be essential for establishing vocational training and life-long learning, particularly so for SMEs. Local specialisation and its specific needs should be addressed, though wherever possible aiming for a pan-European approach.

Roadmap for 2014–2020

Table 1: Disruptive Research

	2014/2015	2016/2017	2018/2019	2020
Critical path from science to innovation	Novel concepts and approaches for materials	Realisation, characterisation	Feasibility	Prototypes
Technological challenges	Set the basis for new materials, functionalities, approaches and processes.	Experimental demonstration of new functionalities and processes.	Demonstration of the industrial potential.	Realisation of first prototypes exploiting new materials and processes.
Research actions	**Nanophotonics:** explore new engineered materials. **Quantum information:** explore new quantum approaches to signal transmission, data processing, and sensing. **Extreme light:** explore potential of light-matter interaction in new regimes.	**Nanophotonics:** realise and characterise simple devices based on the new approaches and materials. **Quantum information:** realise and characterise quantum-based simple integrated circuits as building blocks of future quantum devices and systems. **Extreme light:** realise basic experiments exploiting light-matter interaction in new regimes.	**Nanophotonics:** realise, characterise and qualify integrated devices and systems based on the new approaches and materials. **Quantum information:** realise, characterise and qualify quantum-based integrated devices and systems. **Extreme light:** exploit light-matter interaction in new regimes for material processing, material characterisation, and device fabrication; study the potential of extreme light sources for industrial applications.	**Nanophotonics:** realisation of engineered prototypes based on nanophotonics providing new characteristics and functionalities. **Quantum information:** realisation of engineered prototypes based on quantum optics providing new characteristics and functionalities. **Extreme light:** realisation of engineered sources delivering extreme light and related systems for industrial applications.
Infrastructures and facilities	Define needs for open-access infrastructures and facilities for material development and device fabrication and characterisation; Foster cooperation with existing distributed infrastructures (e.g. LaseLab Europe) and with infrastructures under development (e.g. ELI, Extreme Light Infrastructure).	Realise the needed infrastructures; Strengthen cooperation with existing infrastructures and facilities; Foster cooperation with SMEs on highly innovative projects.	Guarantee open access to infrastructures to both academic institutions, research centres and SMEs throughout time.	Guarantee updating and maintenance of open-access structures.

	2014/2015	2016/2017	2018/2019	2020
Innovation requirements	Define guidelines to make photonics more accessible, eco-friendly, low-cost, capable of efficiently address societal challenges and innovation needs, and of replacing dangerous and scarce materials; Involve photonics-based and photonics-enabled industries to define their long-term needs.	Define specific societal challenges and innovation needs to be targeted in health-care, energy production and saving, high-speed communication, environmental protection, safety and security, remote sensing, advanced imaging, e-services, etc.; Define areas of major market potential.	Involve end-users to define long-term innovation needs for smart cities and communities that can be addressed through photonics; Examine time-to market perspectives and market potential.	Involve all industrial players and end-users to bring innovation to production and market exploitation.
Cross-cutting Key Enabling Technologies (KET) issues	Highly innovative advanced research in photonics has evident synergies with all the other KETs: micro and nanoelectronics (e.g. in photovoltaics); nanotechnology (e.g. in nanophotonics); advanced materials (e.g. in graphene and silicene photonics); biotechnology (e.g. in nanobiophotonics). Advanced manufacturing is also essential. The extent and importance of the possible synergy varies depending on the application field being targeted and the consequent materials and solutions of choice.	Synergies will become deeper and at the same time more specific throughout research evolution towards the realisation of photonic devices and their application.	Hybrid systems employing devices based on photonics and other KETs will be considered to address the innovation needs for smart cities and communities with maximum efficacy.	Synergies of the different KETs will be exploited to address production needs.

Roadmap for 2014 – 2020

Table 2: Education and Training

	2014/2015	2016/2017	2018/2019	2020
Outreach to young minds	Address both kids and secondary school students with specific programs, starting from existing experience (Photonics Explorer, Luka's land of discovery, etc.); Involve teachers in all programs; Organise summer camps; Create a network of outreach-committed centres (academic institutions, research centres, etc.) to sustain and extend actions.	Extend existing programs to new countries through the involvement of local governments; Involve national and international learned societies for support and help in dissemination; Update and where possible and meaningful extend the content of the programs; Involve all-level students through individual awards and team competitions on dedicated problems; Involve industries for sponsorship of outreach programs and of team competitions on specific problems; Involve Science and Technology museums in outreach programs through permanent interactive exhibitions.	Stabilise outreach programs by making them self-sustainable; Strengthen cooperation with learned societies; Strengthen cooperation with industries.	Reach a pan-European dimension for most successful outreach programs and create suitable structures to ensure maintenance.
Outreach to general public	Promote photonics through different media: press, TV, internet, apps, conferences related to art events, etc.; Launch competitions for best videos related to photonics so as to promote direct involvement e.g. of young people (not necessarily studying photonics)	Involve Science and Technology museums to create permanent, interactive exhibitions in photonics (seek for support from companies); Set-up simple but impressive photonics exhibitions in highly crowded environments (such as airports, stations, shopping malls);	Extend successful initiatives, stabilise and maintain them; Involve all possible private and public partners that can make initiatives self-sustainable	Reach a pan-European dissemination of the most successful initiatives

	2014/2015	2016/2017	2018/2019	2020
		Promote local initiatives on special occasions (companies open day, etc.); Promote photonics participation in any local or international initiatives such as day of science & technology; Identify ambassadors for photonics; Set-up photonics-related shows and documentaries.		
Specific programs for technicians (high school; BoSc; vocational training)	Involve local structures (universities, research centres, industries, especially SMEs) and clusters to define needs.	Organise courses mainly targeting SME needs on a local basis; Support smart specialisation initiatives; Involve national and international structures (education and outreach-oriented networks, learned societies, etc.) to exchange best-practice and provide support to extend programs beyond the local level.	Support best initiatives to make them self-sustainable so as to guarantee stability in time.	Support spreading of best initiatives throughout Europe, where needed, while respecting local specificity.
High level education (university & PhD)	Strengthen international cooperation through Erasmus and similar initiatives, mainly at the MoSc and PhD level; Support mobility both for students and teachers; Introduce summer fellowships (3 months); Set standards for basic photonics modules; Strengthen cooperation with industry;	Foster group exercises on specific technological problems and challenges; Promote team work through competition on specific problems of industrial interest; Involve national and international structures (education and outreach-oriented networks, learned societies with student clubs and	Ensure stability and self-sustainability of best initiatives.	Ensure pan-European spreading of best initiatives.

	2014/2015	2016/2017	2018/2019	2020
	Support innovation awards; Foster inter-disciplinary education including photonics, and cross-fertilisation towards applications; Foster exchange of information to support contacts between students and industries.	corporate members, etc.) and industrial partners to favour contacts between students and industries.		
Lifelong learning	Involve local structures (universities, research centres, industries, especially SMEs) and clusters to define needs.	Organise courses mainly targeting SME needs on a local basis; Support smart specialisation initiatives; Involve national and international structures (education and outreach-oriented networks, learned societies, etc.) to exchange best-practice and provide support to extend programs beyond the local level.	Support best initiatives to make them self-sustainable so as to guarantee stability in time.	Support spreading of best initiatives throughout Europe, where needed, while respecting local specificity.

Actions for the implementation of the roadmap

The experience of 7th Framework Program highlighted some critical issues that need to be addressed for a successful implementation of the future roadmaps, both for disruptive research and for education and training.

Disruptive Research

Disruptive research is an essential part of the Excellent Science pillar of *Horizon 2020*. Funding programs should consider the high-risk aspect intrinsic to really disruptive research, together with the importance of having open schemes to help achieve real breakthrough results.

1. Future Emerging Technologies

The FET scheme has already proved to be successful and sufficient. However, some actions could be undertaken to increase its impact within the photonics area. In particular:

- **FET-Open:** Although the adopted fully bottom up approach precludes the introduction of specific topics, it is strongly recommend that the European Commission:
  - raises the number of photonics professionals in the evaluation committee
  - communicates and disseminates photonics related FET Open projects as success stories
- **FET-Proactive:** It is recommended that DG Connect introduces photonics related topics.

- **FET Flagships:** Photonics is already key in some of the FET Flagships projects, hence it is recommended that this activity could be used to enhance communication and dissemination of FET Flagships through attractive ways of communication, audio-visual, etc.. A good visibility of successful photonics projects will foster further actions in the field.

2. ERC grants

ERC grants are traditionally devoted to funding projects of scientific excellence. Although quantum electronics and optics related research have been funded in the past, the scientific excellence underlying photonics technologies seems to have been underestimated. Although specific topics cannot be introduced in the fully bottom up ERC research programme, it is recommended that the European Commission:

- raises the number of photonics professionals in the evaluation committees of the Physical Sciences and Engineering Panel
- communicates and disseminates photonics related ERC Grantees and their projects as success stories
- enhances links between the ERC Scientific Committee and ERC Executive Agency and photonics stakeholders in Europe

B-PHOT's photonics science show for students and teachers where two researchers make a student disappear. © VUB

3. Access to Research Infrastructure

This aspect is fundamental for research institutions and universities to promote mobility of researchers and to ensure efficient usage of facilities. Although ESFRI infrastructures will have a priority under this activity, it is recommended that the Commission facilitates this support through other forms of alliances or networks of research facilities & infrastructures, both specific to photonics and to KETs in general.

Education and Training

Past experience has demonstrated that implementation of successful and effective actions to promote photonics in education and training has been difficult and challenging. In addition to the above recommendations reported, the following aspects should be considered:

1. Outreach

- **Exhibitions and shows:** Exhibitions and shows, fairs and festivals each provide an effective opportunity for the wider popularisation of photonics to the society, and need to be enhanced and provided at a European level. Strategic alliances with committed members allow for the design and implementation of activities, fostering a wide participation from other stakeholders. Connections should be established with existing networks and programs (for example, ECSITE, PLACES, NetS-EU). The involvement of the Commission will be essential for the identification, enabling and evaluation of the actions.
- **'Living Lab' and 'Fab Lab':** Two new concepts are 'Living Labs', allowing some experiments to be performed by visitors under suitable supervision, and 'Fab Labs', allowing tools to be assembled and used by visitors to build some simple prototypes. These should be exploited by Science and Technology museums (and possibly

by academic/research institutions when offering access to the public) as a means of providing a deeper understanding of the technology, and enabling a better knowledge of recent photonics innovations.

- **Prizes:** Different prize awarding models should be considered for motivating students:
  - Teams of youngsters competing in games and competitions on specific topics of industrial relevance, held at a European level and organised by suitable stakeholders
  - Individual prizes following the example of the existing 'Student Innovation Award' promoted by Photonics21
  - Individual or group prizes for activities related to the promotion and dissemination of photonics (possibly also related to non-photonics events, such as art shows, etc.)
  - Individual or group prizes for secondary school teachers in recognition of their commitment to photonics related activities.

2. Higher Education

The European Commission has recently launched a High Level Group on the Modernisation of Higher Education. It is recommended that a strong participation of the photonics community within such a group should be considered, both to bring its experience and to make sure that photonics related issues and needs are taken into account, particularly since these needs will be common to all Science and Technology topics, and in particular to KETs.

3. Mobility of students and young researchers

It is recommended that the Commission increases the number of photonics professionals participating in the evaluation committees of all-level mobility programs, such as Erasmus and Marie Curie actions. It is also recommended that the Commission communicates and disseminates photonics related projects that already exist under different schemes.

Photonics Scienceshow. © VUB

Post-doc scientist using laser light to study fundamental interactions in materials. © Politecnico di Milano

4. Lifelong learning/Vocational training

Several universities, research centres and private companies are already active in offering training and short courses (the latter mainly in connection with large conferences/technical exhibitions) for professionals at all levels, from technicians to R&D and business managers. An effort should be made to create a database of existing modules, so as to define what is already available and what is missing, what can be extended to a European level, and what needs to be addressed on a local basis. This will allow the urgent needs of photonics industry to be addressed through immediate real-time actions.

Our knowledge-based society needs knowledgeable, skilled and well-trained workers, able to sustain continuous improvement and efficient production in science and technology.

Expected impact for Europe

In our knowledge-based society, no real and long-lasting innovation is possible without advanced research to create the basis for future development, and without a wide class of knowledgeable, skilled and well-trained workers, able to sustain continuous improvement and efficient production in both science and technology.

The research areas that have been identified as priorities and now being tackled are likely to revolutionise the field of photonics, bringing new solutions and innovative approaches to address the most difficult of challenges faced in many areas.

The need for sustainable development and a better quality of life requires a green economy, energy efficiency and saving, extended healthcare, safety and security, improved communication, quality and sustainable production, open innovation, environmental care, cultural heritage preservation, etc.. New trends developing in photonics could have a substantial impact in all these fields, including:

- Nanophotonics. Through the development of new and nanoengineered materials with extended optical properties and unprecedented functionalities, nanophotonics offers solutions to many challenges:
  - energy efficiency, through the development of new solutions for photovoltaics, and energy saving, through the realisation of new highly efficient light sources
  - healthcare, through the realisation of smaller functionalised optofluidic lab-on-chips for point-of-care diagnosis, through nanoimaging techniques for advanced diagnostic systems, and by contributing to nanomedicine for example with photoactivated nanoparticles for therapeutic applications
  - safety and security, through the realisation of nanosensors
- Quantum optics and quantum information address the problems related to the management of vast amounts of of data, and to secure communications with completely new approaches exploiting the laws of quantum physics. Feasibility demonstrations have already been achieved, but many technical challenges are still to be solved in terms of adequate light sources and complex quantum circuits, before quantum computers, quantum communication systems, and quantum sensing can become part of everyday life. However, the achievement of such goals would be a major breakthrough for a future digital society.
- Extreme light is expected to open new perspectives in light-matter interactions. The availability of light sources with unprecedented high power, operating in previously unavailable wavelengths and pulse durations will allow the study of materials and processes in unexplored regimes, thus allowing new fundamental knowledge

PhD student aligning a Ti:sapphire laser. © Ruhr-Universität Bochum, Faculty for Electrical Engineering & Information Technology

Vocational training courses for photonics engineers. © Beisert & Hinz

to be developed. Moreover, it will allow major breakthroughs in many applications, such as advanced manufacturing, safety and security, bio-medicine, chemistry, cultural heritage, etc..

Improved education and training offers the following impacts:

- making photonics a popular topic and thus attracting a large number of students will ensure the availability of a future skilled workforce, without which any other efforts would be unsustainable
- extending the presence of photonics-based curricula and of photonics modules within other curricula will contribute to a broadening of the available workforce
- establishing programs for vocational training and life-long learning, primarily targeting the local needs of SMEs, will contribute to a strengthening of European SMEs.

In conclusion, the above actions targeting outreach, education and training at all levels will all have a major impact on European industrial competitiveness, fostering highly innovative SMEs, and ultimately ensuring the continuing success of photonics with the consequent benefits for economic growth and employment.

Actions targeting outreach, education and training at all levels will all have a major impact on European industrial competitiveness.

3

Expected Impact of a Photonics PPP

The overall objective of a Photonics PPP is the establishment of a more competitive photonics sector in Europe. This will be brought about through the following individual areas of impact:

- A Photonics PPP will foster photonics manufacturing, job and wealth creation in Europe through a long term investment commitment by both industry and the European Commission.
- It will pool public and private resources to provide more effective and successful solutions for the major societal challenges facing Europe, in particular for healthcare, the aging society, food safety, security, & energy efficiency.
- Accelerating Europe's innovation process and time to market by addressing the full innovation chain in a number of market sectors where European photonics industry is particularly strong (e.g. lighting, medical photonics, and optical components & systems).
- It will be instrumental in achieving the critical mass necessary for developing a coherent application oriented and market needs driven technology & innovation process.
- Developing and implementing an integrated RDI programme that fully meets the needs and priorities of markets, and tackles the 'valley of death' problem by undertaking strategic projects. Such a strengthened RDI capability will impact the full value chain, from research to manufacturing, and from materials to own-equipment manufacturers & end users.
- Integrating the full value chain into an open innovation approach, ensuring early and meaningful end user involvement from concept to manufacture. The early application of such an interactive value creation process will integrate timely market feedback within a common development process, and thereby help avoid poorly conceived products reaching the market.
- Providing the vehicle for the broader involvement of critical organisations outside of the immediate value chain, including other relevant ETPs & PPPs, capital providers, such as the European Investment Bank and Venture Capitalists.

- Reinforcing links between Photonics clusters in Europe and their respective regional industry and public authorities to align priorities, streamline efforts, and enable smart specialisation and growth in European regions.
- A Photonics PPP will grow photonics manufacturing in Europe thereby creating further 'high skill' employment. This will be achieved by enabling the photonics products themselves to be manufactured in Europe, and by ensuring the ongoing competitiveness of other key photonics-dependent manufacturing sectors in Europe.

A Photonics PPP will result in further photonics solutions for the societal challenges of Europe and will have a direct impact on specific industrial sectors:

Photonics leverages industrial manufacturing

The laser processing industry on its own is a multi-billion Euro industry, and it also has a substantial leverage effect on many other industries, most notably in the European automotive sector.

Lighting solutions foster energy-efficiency

The application of digital lighting solutions would result in annual savings approaching €300 billion of the global energy bill, and savings of 1000 million tonnes of global CO_2 emissions per year [23].

Photonics drives huge OLAE market growth

Growth of the overall OLAE market will rise from its present value of €1 billion to greater than €100 billion.

Major CO_2 emissions savings through virtual presence

Display-enabled rich visual communication for virtual presence could dramatically reduce travel for meetings, resulting in a 20% reduction in business trips in Europe alone, potentially saving 22 million tonnes of CO_2 emissions per year.

Photonic technologies result in advanced visual displays

Global sales of advanced 3D displays will reach €10 billion by 2021, with a 35% share expected for European companies.

Photonic technologies drive healthcare

Photonic technologies could provide a potential 20% cost reduction in healthcare expenditures associated with the demographic changes anticipated in Europe [24].

Photonic sensors increase food safety

The WHO estimates that annually more than two billion illnesses and the deaths of more than two million children are caused by unsafe food [25]; a major reason for this is the absence of a low-cost yet reliable non-contact sensor technology to detect food-borne health threats.

ICT speeds up the knowledge society

Photonic technologies leverage a telecommunication infrastructure market worth €350 billion and impact more than 700,000 jobs in Europe [26].

Expansion of the photonics components and systems markets

The European market share for optical components and systems in the global market place is nearing 50%, and continues to grow steadily.

23 *ICT for Energy Efficiency*, DG-Information Society and Media, Ad-Hoc Advisory Group Report

24 Photonics21 Strategic Research Agenda *Lighting the way ahead*, page 110

25 WHO Reports on Food Safety Issues, *WHO Global Strategy for Food Safety: Safer Foord for Better Health*, World Health Organization, Food Safety Department, Geneva (Switzerland) 2002, ISBN 92 4 154574 7

26 *The Leverage Effect of Photonics Technologies: the European Perspective*, Photonics21

Appendix

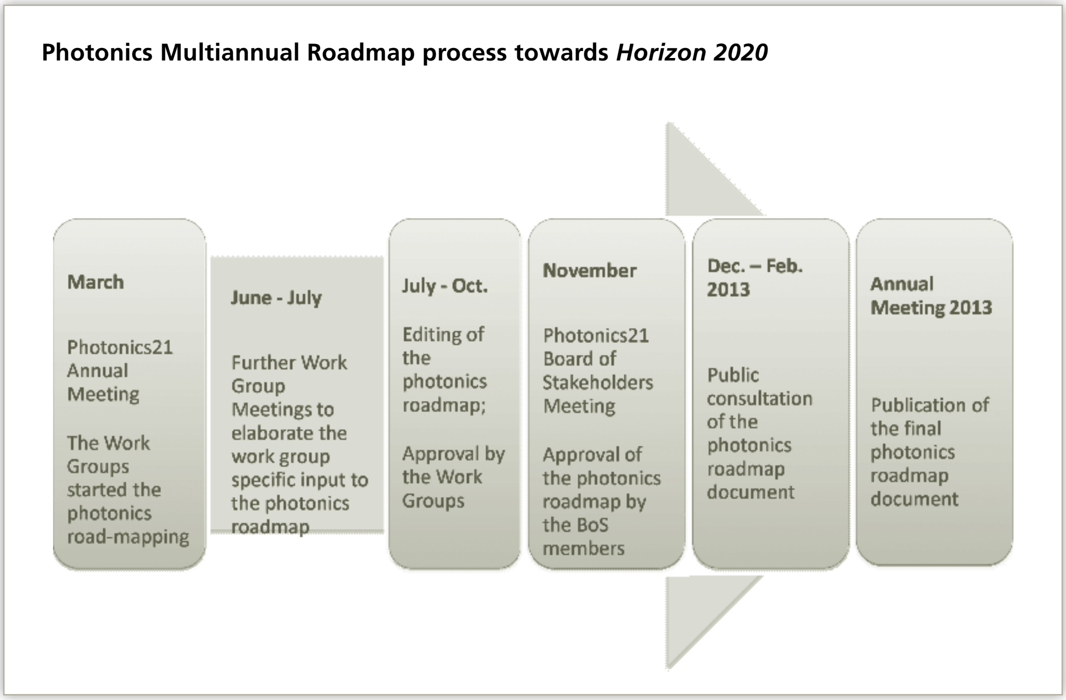
The Photonics Multiannual Strategic Roadmapping Process

The Photonics Strategic Multiannual Roadmap was jointly developed and adopted by the members of the European Technology Platform Photonics21, which represents the European photonics community. The photonics roadmapping process was launched at the Photonics21 Annual Meeting 2012 in Brussels on the 27th – 28th March 2012, and was continued over that year through workshop meetings and open consultation via the Photonics21 website, leading to its publication in April 2013.

The chapters from each Work Group outline their individual roadmap for photonics research & innovation in each of the different photonics application fields addressed by Photonics21:

- Information & Communication
- Industrial Manufacturing & Quality
- Life Science & Health
- Emerging Lighting, Electronics & Displays
- Security, Metrology & Sensors
- Design & Manufacturing of Components & Systems
- Research, Education & Training

The topics and research areas addressed in this photonics roadmap have been selected and discussed by the more than 300 photonics experts attending the seven Photonics21 workshops held during the Photonics21 Annual Meeting 2012. A further seven Photonics21 follow-up workshops have been conducted during June - September 2012 to further elaborate and finalise the photonics roadmap.

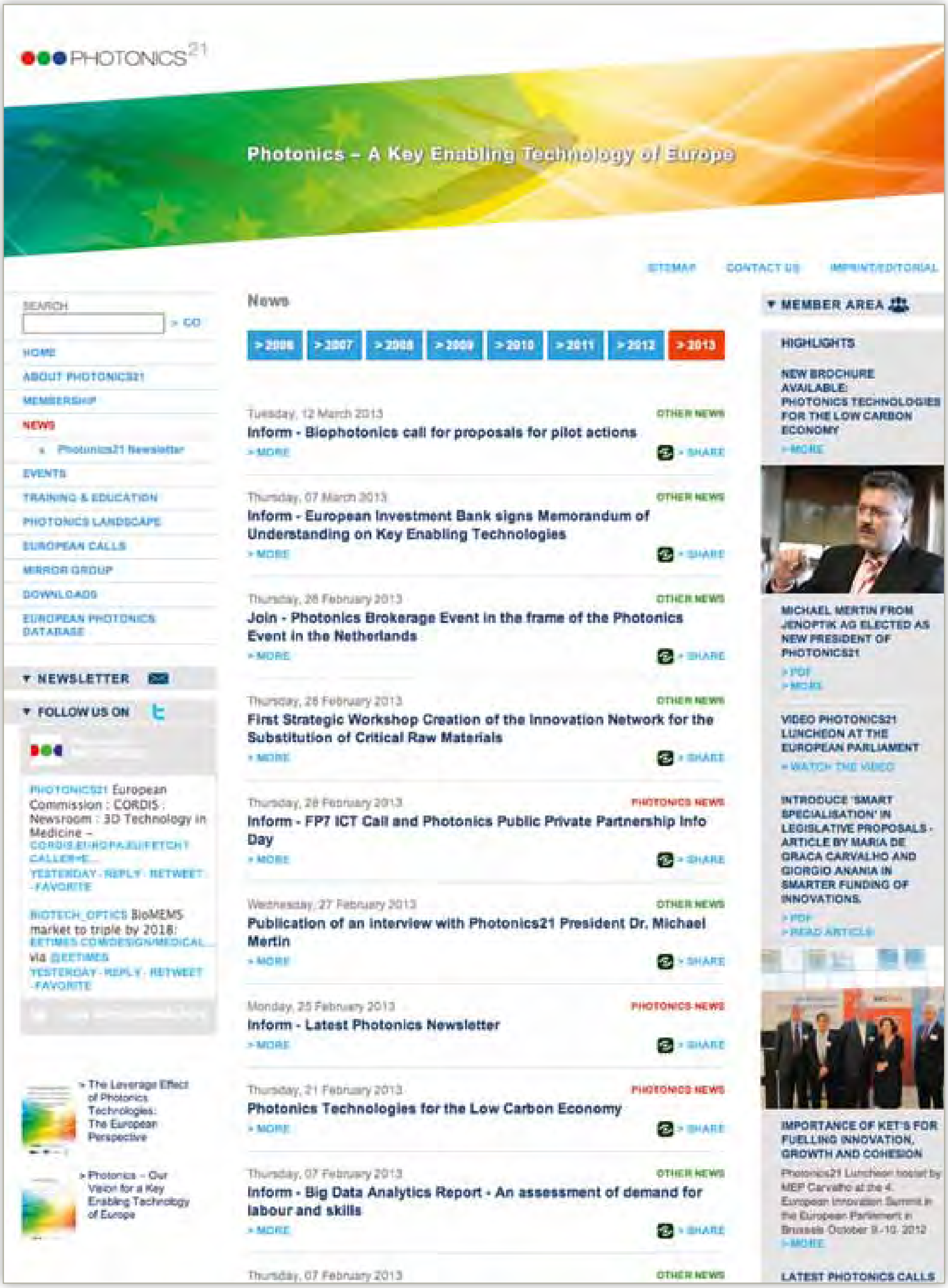


Overview on the Photonics Multiannual Roadmap process.

Communication about the photonics roadmap process

The planning and coordination of the overall photonics roadmapping process was performed by the Photonics21 Secretariat. As part of this process, the Photonics21 Secretariat circulated information on the roadmapping process and workshop events throughout the photonics community. Wide dissemination was achieved using the Photonics21 newsletter and information e-mails, the news & events section and member area of the Photonics21 website (www. photonics21.org), and the recently launched Photonics21 Twitter Channel (https://twitter.com/Photonics21).

The Photonics21 Twitter Channel.

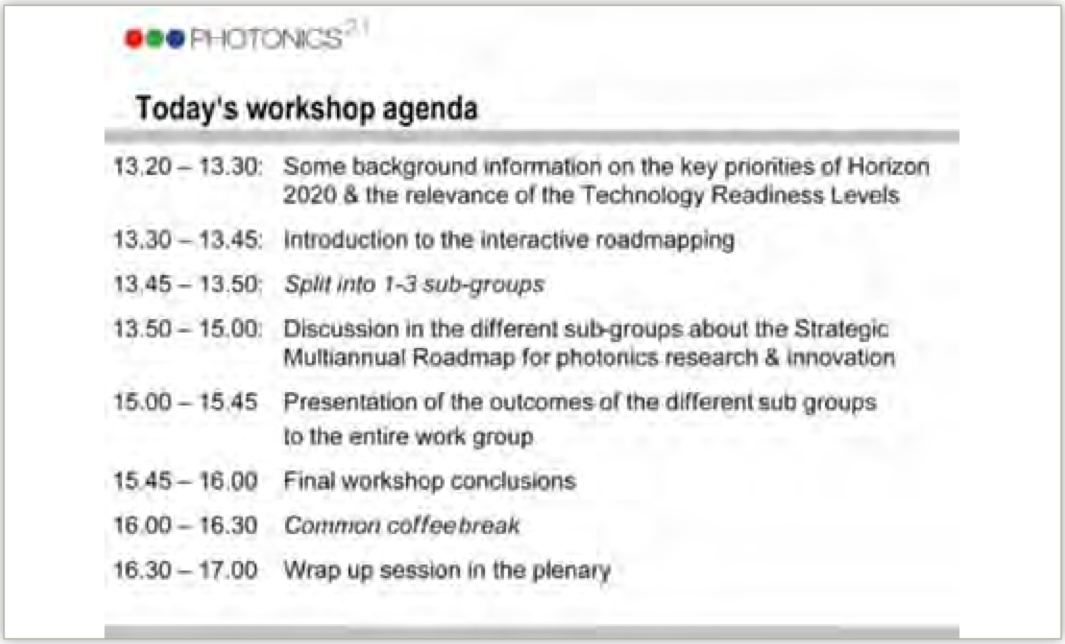


The Photonics21 website – News section. © Photonics21

Interactive workshops & roadmapping process

An interactive workshop concept was adopted for the Photonics21 workshops at the Photonics21 Annual Meeting and follow-up workshops. In these, participants were invited to provide their input and views, which were then discussed, eventually leading to consensus on each Photonics Strategic Multiannual Roadmap section.

Prior to the workshops, the Photonics21 Secretariat had provided all Photonics21 work group members with relevant preparatory material for the photonics roadmapping process.



Figures illustrating the preparatory material for the photonics roadmap process. © Photonics21

Figures illustrating the preparatory material for the photonics roadmap process. © Photonics21

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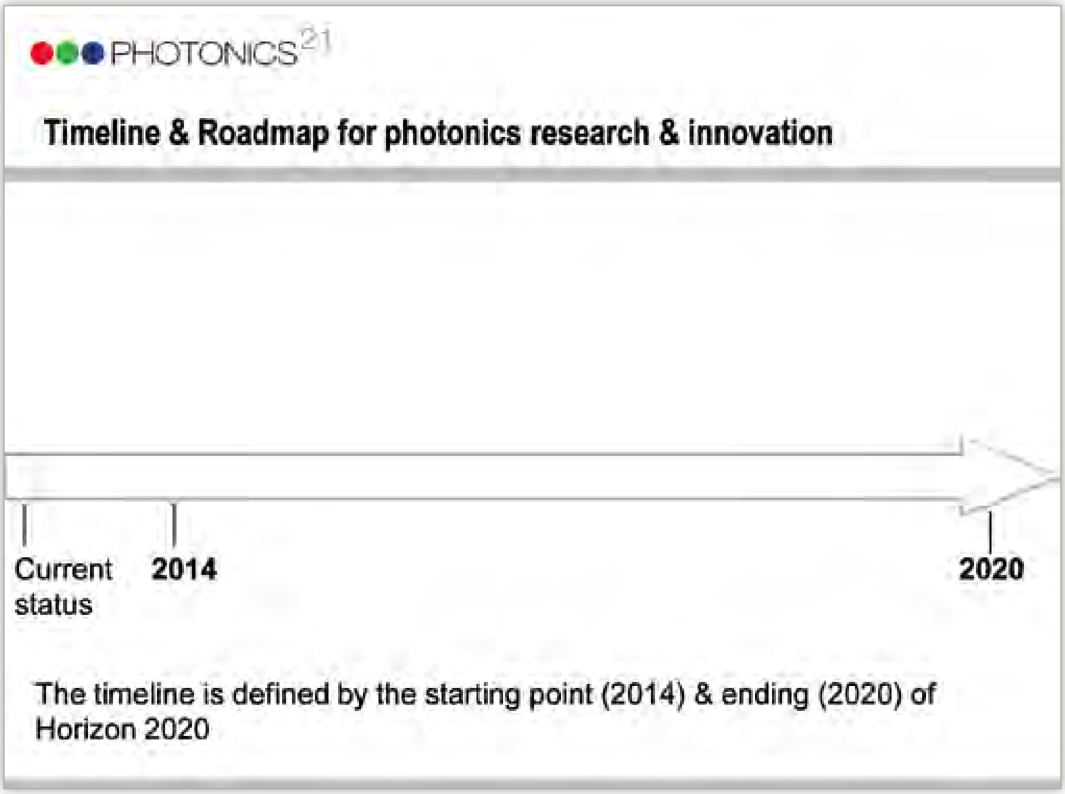
Work Group 4 Emerging Lighting, Electronics & Displays

Major areas of science & technology / **Our vision**	Market uptake of LED technology for lighting	Cost performance breakthrough for OLED & OPV technology	Hybrid System on Foil Integration paving the way to market	Consolidation of Europe's position in selected display market segments
Need for new materials targeting performance enhancement				
Need for better components, device integration & system architectures to serve the needs of the different applications targeted				
Need for sustainable, low-cost manufacturing methodologies & platforms				



PHOTONICS21

Draft structure - Photonics21 Strategic Multiannual Roadmap

Introduction	(~5 pages)
Strategic Objectives and Vision	
Key Performance Indicators	
The Roadmapping Process	
Photonics innovation ecosystems in Europe (Industry, Research organisations, Clusters, NTPs, etc.)	
Photonics Research and Innovation Challenges	(~42 pages)
Information & Communication	(~6 pages)
Industrial Manufacturing & Quality	(~6 pages)
Life Science & Health	(~6 pages)
Emerging Lighting, Electronics & Displays	(~6 pages)
Security, Metrology & Sensors	(~6 pages)
Design and Manufacturing of Components & Systems	(~6 pages)
Education, Training & Disruptive Research	(~6 pages)
Expected impact of a Photonics PPP	(~2 pages)
Annex	(~1-2 pages)

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Draft structure - Work Group 1 chapter

Photonics Research and Innovation Challenges
Information & Communication

Main socio-economic challenges addressed	(~0.5 page)
Major photonics needs	(~0.5 page)
Involvement of value chain partners (outside Photonics industry/research)	(~0.5 page)
Major photonics research & innovation challenges	(~2 pages)
Roadmap for 2014 – 2020	(~1.5 pages)
Expected impact for Europe	(~1 page)

Figures illustrating the plan for Photonics21 roadmap documents. © Photonics21

Figures illustrating the plan for Photonics21 roadmap documents. © Photonics21

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Draft structure Work Group 1 Proposed roadmap for 2014 - 2020

	2014/2015	2016/2017	2018/2019	2020
Critical path from science to market	Novel concepts & approaches for components and systems	Realization, characterization & demonstration of novel components	System design, integration & verification	Demonstration & application of complete system solutions
Technological challenges				
Research actions (Which solutions should be investigated?)				
Innovation requirements (Instruments) Pilot & demonstration actions; Value chain end users to involve; Market potential; Appropriate innovation models (open, social innovation)				
Cross-cutting Key Enabling Technologies (KET) issues Pilot & demonstration Actions; Outline synergies with the other KETs				

Development of the photonics roadmap

Following the Photonics21 workshops, each work group chair set up an editorial group that was responsible for providing a first draft of the work group specific roadmap chapter. These draft chapters were then circulated to the individual Photonics21 work group members for further comments and feedback. Additionally, all relevant materials for the photonics roadmap process were uploaded onto the members' area on the Photonics21 website. This area is accessible to all Photonics21 members, thereby ensuring an open and transparent process for roadmap definition.

The development of the photonics roadmap drew extensively on the following two Photonics21 strategy documents, each outlining future European photonics research and innovation challenges:

- Lighting the way ahead
  - the Second Strategic Research Agenda for Photonics, (Jan 2010)
- Photonics – Our Vision for a Key Enabling Technology of Europe
  - the Photonics21 Vision Document, (May 2011).

The Photonics Strategic Multiannual Roadmap builds on these documents to identify research and innovation areas and priorities for the coming years, and it will serve as the strategic reference document for the Photonics PPP in the new Framework Programme *Horizon 2020*.

Photonics21 Publications *Lighting the way ahead* & *Photonics – Our Vision for a Key Enabling Technology of Europe*. © Photonics21

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