nanophotonics europe association

NANOPHOTONICS
A FORWARD LOOK

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About this Report

This document is the report of the Nanophotonics Europe Association workshop held at King's College, London (UK) in July 2012. The purpose was to define a strategy for advancing research and development of nanophotonics. The views, ideas, conclusions and recommendations presented in this report are those of the workshop participants.

Nanophotonics Europe Association

The Nanophotonics Europe Association (NEA) is a not-for-profit organisation created to promote and advance European science and technology in the emerging area of nanophotonics. The goals of the association are fourfold:

1. To promote research in nanophotonics by coordinating the efforts of the various players involved, and, in particular, by encouraging collaboration between academic institution and industry.

2. To create a common interest group that represents member's interests with national and transnational scientific government funding agencies, technology platforms, professional associations and the general public.

3. To integrate the resources and strategies of its members.

4. To facilitate the exchange of information, ideas and data.

More information can be found on the NEA website:
www.nanophotonicseurope.org

Executive Summary

Nanophotonics is concerned with the application of photonics at nanoscale dimensions, where field enhancement effects result in new optical phenomena offering superior performance or completely new functionalities in photonic devices. Nanophotonics is an enabling technology that has the potential to impact across a wide range of photonics products ranging from high efficiency solar cells, to ultra-secure communications, to personalized health monitoring devices able to detect the chemical composition of molecules at ultralow concentrations.

This report summarises the conclusions of the Nanophotonics Foresight Workshop held in London, UK, July 2012 to define a strategy for advancing research and development of nanophotonics within the European Commission's 'Horizon 2020' funding initiative.

A number of representative example potential applications of nanophotonics are presented to illustrate the potential commercial and/or societal impact of these technologies.
These are:

1. Nano-Engineered Photonics Materials
2. Nanoscale Quantum Optics
3. Nanoscale Functional Imaging
4. Photovoltaics
5. Communications & All-Optical Signal Processing
6. Chemical/Biosensors
7. Plasmon-Enhanced Magnetic Storage

Research into nanophotonics is actively addressing potential applications across a wide range of subjects, but the connection to European industry is still relatively weak. If these connections can be strengthened, European industry will be in an exceptional position to exploit nanophotonics and to deliver novel technological solutions.

To ensure appropriate representation of this disruptive technology within Horizon 2020, the nanophotonics community needs to interact effectively with the Photonics21 working groups and so have a direct influence on the definition of the PPP roadmap.

Targeted support is required in three main areas:

- Fundamental research in the underlying physics of nanophotonic interactions
- Cost-efficient nanofabrication and nanopatterning methods with nanometre dimensional control
- Development and optimization of application-specific photonics devices and systems

The disruptive nature of nanophotonics is such that many of its ultimate applications are not yet known. Therefore, in addition to supporting the areas where nanophotonics already has clearly identified potential for addressing societal challenges, targeted support for curiosity-driven research will also be essential to allow other new uses to be identified and developed.

Underlying support for developing a dynamic and productive nanophotonics community in Europe should be provided through establishing suitable infrastructures, and by promoting training and outreach activities in the area.

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This report highlights seven specific nanophotonics research areas, each offering significant commercial or societal impact, and summarises their relevance, technology challenges and outline 7-year roadmaps, in line with the roadmaps being prepared by Photonics21.

What is Nanophotonics and why is it important?

Nanophotonics is concerned with the application of photonics at the nanoscale. As light is squeezed down into nanometer scale volumes, field enhancement effects occur resulting in new optical phenomena which can be exploited to challenge existing technological limits and deliver superior photonic devices. Nanophotonics encompasses a wide variety of topics, including metamaterials, plasmonics, high resolution imaging, quantum nanophotonics and functional photonic materials. Previously viewed as a largely academic field, nanophotonics is now entering the mainstream, and will have an increasing role in the development of exciting new products, ranging from high efficiency solar cells, to personalized health monitoring devices able to detect the chemical composition of molecules at ultralow concentrations.

Horizon 2020 and the Photonics Public-Private Partnership

Horizon 2020 is the EU's new Framework Programme for research and innovation aimed at securing Europe's global competitiveness and creating new growth and jobs in Europe. This seven year programme will run from 2014 to 2020 and has an estimated €80 billion budget. Specific focus will be directed towards solving the major societal challenges facing Europe, and bridging the gap between research and the market.

The Photonics21 platform is establishing a Public-Private Partnership (PPP) with the European Commission with the following objectives:

- Foster photonics manufacturing, job and wealth creation in Europe through a long term investment commitment by both industry and the European Commission
- Accelerate 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)
- Pool public and private resources to provide more effectively successful solutions for the major societal challenges facing Europe, in particular in healthcare & energy efficiency

The Photonics PPP will play a pivotal role in determining the work plans for photonics research, development & innovation calls within Horizon 2020, planned over the next seven years. It will also benefit from photonics having been identified in 2009 as being one of the Key Enabling Technologies (KETs) that will shape European industry over the next 5 to 10 years. The seven Photonics21 working groups are developing the initial technology road map for the Photonics PPP, based on detailed analysis and discussions with their membership. This is where inputs from the nanophotonics community should be directed for maximum impact.

Highlighted Applications of Nanophotonics

The enabling nature of nanophotonics means that the potential applications of nanophotonics will be broad. Therefore, a number of representative examples are presented, and whilst not constituting an exhaustive list, these serve to illustrate the potential commercial and/or societal impact of nanophotonic technologies, and are recommended for targeted support.

These are:

1. Nano-Engineered Photonics Materials
2. Nanoscale Quantum Optics
3. Nanoscale Functional Imaging
4. Photovoltaics
5. Communications & All-Optical Signal Processing
6. Chemical/Biosensors
7. Plasmon-Enhanced Magnetic Storage

The order of presentation has no particular significance.

1. Nano-Engineered Photonics Materials

Main socio-economic challenges addressed

Photonic nanomaterials are expected to have a major impact for several European Societal Challenges:

Inclusive innovation and secure society - advanced security and surveillance via low-cost, high efficiency image sensors and photodetectors

Reliable, clean and efficient energy - novel nanomaterials and nanostructured multifunctional surfaces for high efficiency photovoltaics and light generation (solid-state lighting)

Health, demographic change and wellbeing - novel materials for photonic sensors and actuators for remote health monitoring.

Fig 1
Quantum Dot Dyes
Courtesy of ICFO. Picture by Fotolia

Major photonics needs

The major photonics needs in the field of photonic nanomaterials are:

- Multifunctional nanostructured surfaces for advanced photovoltaics (PV), touchscreen and tactile display applications providing surfaces with multiple functionalities (such as improved light trapping, controlled optical emissivity, colour filtering/sorting), improved mechanical/chemical properties (impermeability, anti-microbial properties, flexibility, robustness), and self-cleaning/self-healing properties

- Advanced nanomaterials for IR sensing and imaging that are high efficiency and low-cost, integrateable with CMOS electronics. Examples include carbon nanotubes for microbolometer applications, colloidal quantum dots for IR-sensors, and graphene as a novel transparent electrode for sensors and as a novel photodetector material

- Composite multifunctional and tuneable optical materials and filters for hyperspectral imaging and sensing

- Control and tuneability of light manipulation at the nanoscale via coupling of photonic and plasmonic functionalities with advanced nanostructured materials (metals, hybrid metal-semiconductors, graphene)

- Advanced non-linear materials for optical switching, data processing and frequency conversion (with the non-linearity enhanced by nano-structuring), nanoscale employment of plasmonics, and optical field concentration

- Novel optoelectronic nanomaterials for low-cost large area PV, displays, lasers, photodetectors (using nanophosphors, quantum dots, organics)

- New design capabilities, for example inspired by transformation optics, and affordable nano-fabrication & manufacturing infrastructure,

Involvement of value chain partners

The value chain partners to be involved are:

- Imaging sensor industry
- Advanced nanofabrication industry
- Advanced nanomaterials chemical industries
- PV industry
- Defence and security industry
- Optoelectronics and photonics industry

Major Photonic Research and Innovation challenges

The challenges identified within the Photonics21 agenda related to cutting edge materials and technologies are found in the areas of enhanced storage, infrared absorbers, non-linear and optical switchable meta-materials, graphene photonics and tuneable & controlled optical emission and absorption for light harvesting, and displays.

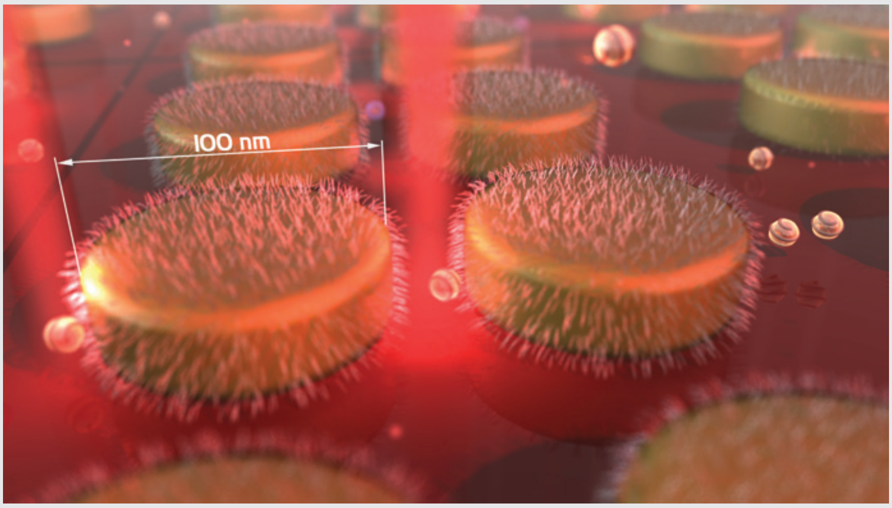

Fig 2
Nanomaterial Growth
Courtesy of ICFO. Picture by Digivision

Roadmap for 2014 - 2020

	2014/2015	2016/2017	2018/2019	2020
Critical path from science to market	Identify market opportunities and industries for novel materials and processes in EU	Identify production technologies adaptable to large scale top-down (NIL) & bottom-up manufacturing, colloidal chemical synthesis	Create market needs and pass on upscale and commercialization strategies	Generate SMEs and industries to make demo products with appropriate funding support
Technological challenges	Large area low cost fabrication of multi-functional materials for high performance displays, windows, screens, solar cells, etc.	Controlled properties of bottom-up nanomaterials (QDs, CNT, graphene) for novel optoelectronic devices (safety, security, health, surveillance, communications)	Low cost fabrication of advanced photonic nanostructures (metamaterials, plasmonic structures) For solar cells, biosensors, photodetectors	
Research actions	Investigate novel materials with tailored optical-plasmonic properties (tuneable absorption & emission, non-linear properties)	Combined electronic tuning in the photonic properties of the materials		Create/exploit new physics for combining classical and quantum properties of materials for hybrid light matter interactions
Innovation requirements	Increased light trapping Improved non-linearities For wavelength conversion	Co-optimization of electronic and optical properties of novel Nanomaterials (QDs, graphene, metallic nanostructures)	Multifunctionality Demonstration: optical and mechanical properties (friction, robustness, impermeability)	Novel hybrid nano-materials based on metal-semiconductors. Graphene nanostructures for control of light-matter interactions
Cross-cutting KET issues	Interact with advanced materials and nanophotonics communities	Involve PV community to address challenges	The role of nanotechnology KET to nanophotonics and vice versa	

Expected impact for Europe

Advances in novel photonic nanomaterials are expected to:

- Radically boost European scientific excellence bringing Europe to the forefront of high-tech added-value product technology
- Develop novel high-tech SMEs and large industries working on the synthesis and fabrication of novel materials
- Expand the European PV-industry
- Expand the European photonic IC industry
- Grow the European lighting industry in displays and solid-state lighting

Focus should be given to the training of new researchers that will be needed to tackle the multidisciplinary nature of expertise essential for the development of next generation advanced nanophotonic products.

2. Nanoscale Quantum Optics

Main socio-economic challenges addressed

Inclusive, innovative and secure societies - the grand challenge for nanoscale quantum optics is the development of components for quantum communication and quantum computing. Quantum cryptography provides an intrinsically secure and unbreakable code, and has been demonstrated both inside and outside the laboratory up to modest video speeds and over modest distances (tens of km). Quantum computing has only been demonstrated in the lab, and only up to about ten quantum bits, using complicated systems that require low-temperature vacuum operation. Nanophotonics can improve both technologies and make them readily available for room temperature operation. The potential applications of quantum computers are enormous, as these computers promise an exponential speed-up of important processes such as the factorization of large numbers and fast searches in large databases.

Reliable, clean and efficient energy - as quantum optics forms the basis of all light-matter interactions, theoretical and experimental breakthroughs in this field will be beneficial to the whole community. Significant improvements in the quantum efficiencies of photovoltaic devices and LEDs are anticipated.

Smart, green and integrated transport - although good (mechanical) quartz clocks and excellent but expensive (optical) atomic clocks are in existence, there is a huge gap (up to 6 orders of magnitude) between their respective levels of performance. The accuracy of global positioning systems (GPS) is currently limited by clock performance, so a more accurate but economic clock based on nanophotonics would enable next generation GPS with wide potential applications in future integrated transport systems.

Major photonics needs

There is a major need for a better and more convenient material system for quantum bit (qubit) operations. Although there are several promising candidates, such as spins in semiconductors, and large organic molecules, none of these systems is ideal. In comparison, the optical quantum bit, in the form of the polarization of a single photon, is very robust and easy to manipulate and detect. The ideal material qubit system has a lifetime-limited optical transition, exhibit negligible de-phasing, and is typically located in an optical cavity to boost the atom-field interaction and so direct the optical field. Room temperature operation would be advantageous.

Involvement of value chain partners

Industrial partners from the (classical) computer industry and telecom are likely candidates to participate. Microsoft has already demonstrated its interest with the investment of €1M in a Dutch research group working on quantum computers, and other industry players will soon join the race. In particular, several European companies, such as ID-Quantique (*www.idquantique.com*) and SELEX-SI-Finmeccanica (*www.selex-si.com*), have become world leaders, pioneering quantum computing schemes and implementing various forms of quantum cryptography over distances up to hundred km. Although the payback time may be relatively long, the rewards are potentially high in terms of a revolutionary new technology and securing future jobs.

Major photonics research & innovation challenges

The main challenge for both quantum communication and quantum computing lies in the development of new components offering improved performance and greater ease of use. Examples include single-photon sources, sources that generate quantum-entangled states, conditional switches, and quantum memories. The ideal component exhibits strong interaction at the single-photon and single-atom level, operates at room temperature, and can be integrated on a chip. Optical antennas and nanoparticles will be important tools to strengthen the light-matter interaction. A significant role for plasmonic devices is foreseen for exhibiting nonlinear behaviour at the single quantum level.

Roadmap for 2014 - 2020

	2014/2015	2016/2017	2018/2019	2020
Nanoscale quantum computer	One nanophotonic quantum bit	Two coupled nanophotonic qubits	Multiple coupled qubits integrated on a chip	Small quantum computer integrated on a chip
Quantum cryptography	Q-cryptography at video speeds over tens of km	Development of optical memories and quantum repeaters	Implementation in fibre and satellite based quantum communication	Q-cryptography at video rates across the oceans
Single-photon sources & CNOT gate	Efficient single photon sources that emit in a random fashion	Controlled single-photon emission in nanoscale sources	Development of solid-state single photon source with better performance	Easy-to-use single-photon sources and CNOT gates integrated on a chip
Metrology (measuring frequency, time)	Development of accurate and practical optical oscillators	Better and more convenient oscillators	Nanophotonic solid-state frequency standard	Reliable nanophotonic oscillator on chip
Plasmonic devices for quantum and nonlinear operations	Efficient optical devices benefit from evanescent (plasmon) field	Nonlinear plasmonic devices at lower power levels	Active plasmonic devices incorporate optical gain	Q-plasmonics switches operating with single quanta

Expected impact for Europe

The potential for quantum computers is enormous, as these computers promise an exponential speedup of important processes such as the factorization of large numbers and searches in large databases. In addition to being unbreakable, quantum communication is the only means of communication that maintains the quantum nature of the information.

3. Nanoscale functional imaging and spectroscopy

Main socio-economic challenges

Health, demographic change and well-being - nanophotonics will impact this challenge in a number of ways:

- The development of preventive and personalized medicine will be critical for solving the challenges of an aging society and increasing population
- Diagnostics tools that are cheaper, more specific and more sensitive will improve healthcare and reduce costs
- The development of novel therapies based on molecular biology & bionics
- The development of artificial intelligence for continuous and wearable monitoring systems
- Studying and manipulating the cell membrane protein structures with nanometer resolution for in-vitro protein-protein interaction using optical methods combining super-resolution, sensitivity, specificity and throughput

Food security, sustainable agriculture, marine and maritime research, and the bio-economy - the development of cheaper, more specific and more effective screening tools based on nanophotonics will provide enhanced protection against diseases and contamination, supporting food security and sustainable agriculture.

Inclusive, innovative and secure societies - the development of continuous and wearable monitoring systems and artificial intelligence based on nanophotonics will also contribute to solving this challenge.

Major photonics needs

- Improved imaging tools for biologists, biochemists and materials scientists with 5-10nm spatial resolution for individual proteins cell membrane manipulation, and more sophisticated interfaces for photo-induced life science processes
- Faster and more sensitive light detectors
- New probes/markers and assays suitable for nanoscale functional imaging (fluorophores, nanoantennas, surface enhanced Raman spectroscopy [SERS] substrates)
- Ultra-compact integrated systems for lab-on-chip applications

Involvement of value chain partners

- Biotechnology industry for the development of assays that exploit nanophotonics and nanotechnology, and for the development of brighter fluorophores & techniques for in-vitro placements.
- Pharmaceutical industries to support long-term nanophotonics research projects.
- Academic and research centres to establish partnership with biologists and bio-imaging centres to facilitate closer with the nanophotonics community.
- Improved interaction with materials scientists to develop the use of optical nanoscopies for investigating organic materials and their blends.

Major photonics research & innovation challenges

Clearly, the application of optical techniques to life sciences should be aligned with the needs of biologists, and this requires a bridging of the existing gap between the photonics and biology communities, especially so for nanophotonics. Often the biologist finds the adoption of a new photonics technique difficult because of complexity in the optical setup or in the assay development, and greater effort is required to provide a simple plug and play system. Moreover, the area is still quite explorative and many options exist. Direct interaction with end users will allow early identification of the most promising techniques, hence shortening the time to market.

The optical antenna concept is very promising for achieving ultrahigh spatial resolution and sensitivity, but requires development for real-world applications. In particular, issues to be addressed include scanning speeds & data handling for the required specificity & throughput, cost and reproducibility of nanofabricated single element and array antennas, and wavelength of operation, where operation in near-IR offers significant performance advantages.

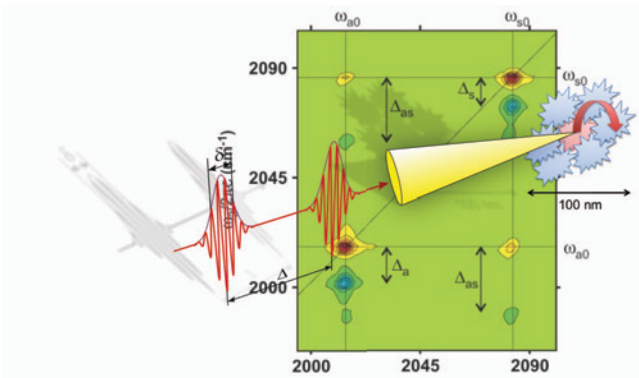

Fig 3
Schematic of a Nanophotonic Antenna for Advanced Nanoscopy
Courtesy of LENS, figure adapted from David M. Jonas, "Two-dimensional femtosecond spectroscopy," Annual Review of Physical Chemistry 54, 425 (2003)

The use of nonlinear and time-resolved techniques in optical nanoscopy offers further breakthroughs in biology and materials science, and the nanoantenna concept offers substantial improvements in terms of sensitivity and resolution. This requires theoretical work to understand the construction of spectroscopic signals in terms of the spatial, temporal and polarization profiles of excitation fields, as well as development of optimized application specific antenna designs.

Nanophotonics will also play an important role in the development of hybrid interfaces between living cells and artificial devices, for example, electrically stimulating a neuron via an optically excited photoconductive polymer. The possibility of achieving nanoscale control of the excitation light could lead to an unprecedented level of control of living functions at the sub-cellular level, thereby enabling a wide range of applications, such as new diagnostic tools for lab-on-chip devices and artificial intelligences.

Roadmap for 2014 - 2020

	2014/2015	2016/2017	2018/2019	2020
Critical path from science to market for functional nanoscopy and spectroscopy	Novel concepts and approaches for components and systems	Realization, characterization and demonstration of novel components	System design, integration and verification	Demonstration and application of complete system solutions
Technological challenges	Nanofabrication of antenna probes	Reproducibility of probes and setup implementation	Lifetime of antenna probes	Alignment and scanning, throughput
Research actions	Invest in existing and novel nanofabrication methods, nano-optical investigation of the fabricated probes	Optimize the probes and start to implement a variety of spectroscopic techniques	Provide feedback to nano-fabrication from the point of view of the spectroscopic signal, bench-mark the technique	Reduce the complexity of the setup, increase the acquisition rate
Innovation requirements	A nanoantenna with an optical resolution of 5-10 nm	Background suppression in a dense sample. High throughput in excitation and collection channels	Increase the robustness and stiffness of the antenna, especially of the sharp features	A real-world stabilization system
Cross-cutting KET issues	Working wavelength, resolution, working environment (liquid/air) are determined by the application field	Heating, photobleaching and overall degradation of the sample. Autofluorescence in real-world applications.		

Expected impact for Europe

The deployment of the nanoantenna technology for nanoscale functional imaging and spectroscopy would:

- Support industrial leadership and job creation by generating innovative products and new markets (worldwide) for high-tech SMEs
- Advance biotechnology and life sciences by providing new tools for biologists and biochemists. This would also innovate educational programs and create leadership in an emerging field at the interface between optics, photonics, life sciences and materials sciences

These benefits will eventually influence other key sectors, such as diagnostics and therapeutics, PV, hydrogen storage, and strengthen the competitiveness of European companies worldwide

4. Photovoltaics

Main socio-economic challenges addressed

One of the major applications of nanophotonics, and certainly one with major immediate potential for commercial, economical and societal impact, is its use for enhanced performance photovoltaics (PV). Specifically, nanophotonic PV will contribute directly to the following European Societal Challenges:

Secure, clean and efficient energy and Climate action, resource efficiency and raw materials - photovoltaics will be a critical technology for both these challenges, offering a renewable source of clean, non-polluting energy, with consequent benefits for climate action.

Inclusive, innovative and secure societies - dependence on non-EU countries for energy supply will be reduced.

Fig 4
Photovoltaic Solar Panel Array
Courtesy of University of St Andrews

Major photonics needs

Photovoltaics convert photon energy from the sun into electrical energy. One of the major challenges of the PV sector is to achieve high conversion efficiencies at low cost. Grid parity is the best measure of overall PV efficiency including the cost of manufacturing. Therefore, to achieve grid parity with other energy sources, it is necessary to capture as much of the incident solar energy (maximise efficiency) in the minimum amount of PV material (minimise cost). Improving PV cell efficiency has become a (nano)photonics challenge of making the active region thin while keeping the absorption efficiency high to make every photon count! Several approaches can be used to control the interaction of light using sub-wavelength structured surfaces (i.e. nanophotonics). Quantum well structures can be grown to engineer the absorption bandgap of each layer. Quantum dots in organic and semiconductor materials offer greater flexibility for bandgap, current and strain management to achieve higher conversion efficiencies. Quantum dots can also be used to generate intermediate-band PV material for multiple-wavelength band cells, etc. To achieve these advances, better control of uniformity in size, form and symmetries of quantum dot nanostructures will be required.

Involvement of value chain partners

The industrial ecosystem created would include:

- Photovoltaics panel manufacturers – for example, Oerlikon, ST Microelectronics, Sharp, Nanosolar, etc.
- Materials industries – for example, Schott, BASF, Saint-Gobain, Merck, Bayer, etc.
- R&D Organizations – for example, ECN, U Eindhoven, Fraunhofer ISE, IMEC & IMOCMEC, CEA, LIOS, U Groningen, U Linköping, etc.

Major photonics research & innovation challenges

The key photonics challenge for PV is to channel every photon into the thin film to ensure complete absorption, and nanostructuring offers an attractive route for achieving this. The major challenge is that nanostructuring must be done cheaply and on large area substrates, and without impacting the electrical properties of the material. The optimum nanostructure to achieve this goal requires investigation.

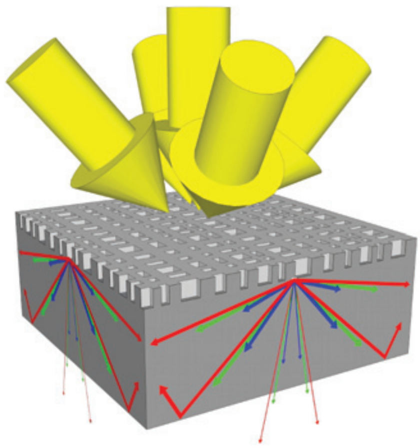

Fig 5
Solar cell with nanostructured surface to increase light absorption
Courtesy of University of St Andrews

Novel solutions, such as non-III-V multi-junction cells (III-V might be excluded for cost reasons), intermediate bandgap solar cells, and thermo-photovoltaics need to be explored.

Roadmap for 2014 - 2020

	2012	2014/2015	2016/2017	2020
Scientific Challenge: *What is the best nano-structure to use for low $/W PV? How not to compromise electrical performance?*	Researchers from multiple disciplines (materials, engineering, photonics)	Reach density of states limit for absorption: Every photon counts! Novel concepts assessed, e.g. non - III-V multijunction, intermediate bandgap, Thermo-PV	Demonstrate equivalent electrical properties of nanostructured vs. non-nanostructured PV materials	Approach the Shockley-Queisser efficiency limit in a thin film
Technological Challenge: *How to print nano-structures cost effectively?*	Better links between photonics researchers & PV industry	Achieve 15% efficiency for thin film Si Demonstrate large area nanostructuring	Achieve 15% efficiency for large area thin film Si	Achieve 20% efficiency for large area thin film Si
Funding challenge: *No dedicated photonics funding in EPIA or in Photonics21*	Dedicated calls for Nano-PV; Include nanostructured detectors in Ph21 WG5	Dedicated calls for Nano-PV; Carbon tax funding	PPP Funding for Nano-PV	

Expected impact for Europe

European industry needs innovative solutions to compete against under-priced Asian manufactured cells that are now flooding the market.

European researchers can establish a research lead in novel nanophotonics structures for PV.

Achieving a cost effective efficient PV technology would open up an enormous market for European industry, with consequent benefits for employment. Estimates for the number of European PV-related jobs in 2020 range from several hundreds of thousands up to a million depending on the European market share achieved for global manufacturing and installation.

5. Communications & All-Optical Signal Processing

Main socio-economic challenges addressed

The application of nanophotonics to optical communications and all-optical signal processing will make significant contributions to several European Societal Challenges:

Inclusive innovation and secure society - through faster data communication, faster and more energy efficient supercomputers & datacentres, and faster optical communication routers

Reliable, clean and efficient energy - through reduction in energy consumption of the supercomputers, datacentres, and routers

Health, demographic change and wellbeing - through the use of the nanophotonics technology in the areas of integrated bio-medical devices, gas sensors, and bio-analysis

Major photonics needs

Currently, the development of integrated circuits for optical communications sees a strong trend towards silicon (Si) photonics, and a convergence of photonics and electronics (via common fab processing, high-level design tools, packaging, and even through application as short range datacomms). Nanophotonics for optical communications and all-optical signal processing would capitalize on this convergence. CMOS-compatible nanophotonics components will provide more efficient all-optical functions, such as all-optical signal routing and processing for packet header recognition, allowing key electronic device functions to be realized on a nanophotonic platform. CMOS-compatible nanophotonics would include integrated plasmonics, metamaterials, graphene, and Si photonics, each offering compatibility with CMOS fabrication.

Two major application areas are envisaged:

- *Nanophotonic functional devices for integrated photonics* - aimed at the reduction of power consumption and increase of speed in macroscopic photonic networks by providing the enhanced functionalities not-achievable using standard macroscopic approaches. These include enhanced nonlinear response at low powers, control of dispersion, and 3R processing (reamplification, reshaping, & retiming) of signals. In this case the advantage of nanophotonics is not the intrinsic size, but rather the enhanced light-matter interaction possible at the nanoscale.

  Requirements for this application are: i) no absolute need for CMOS compatibility, ii) integrability with fibre/planar photonic circuits, and iii) low insertion loss.

- *Nanophotonic components integrated into CMOS photonic / electronic circuitry* - the integration of photonics and electronics will reinforce the strengths of the two domains, whilst compensating for their respective weaknesses. This will allow increased data transfer rate compared to pure electronic devices, reduced energy consumption on a chip, and provide additional functions in terms of modulation, switching, and 3R processing of signals. The ultimate goal will be a true photonic network on an interposer chip connecting the electronic components of a system-in-a-package.

  Requirements for this application are: i) CMOS-compatible materials, and ii) design rules compatible with existing microelectronic design rules.

Strong links should be created between fundamental researchers and large industry players. Access to CMOS foundries by researchers and SMEs should be facilitated to allow adaptation of existing processes and the development of specific Si photonic fabrication steps.

Involvement of value chain partners

Although mainstream microelectronic foundries and most known supercomputer companies lie outside of Europe, Europe still has huge industrial assets and an excellent R&D environment to support assembling the whole food chain of CMOS-compatible photonics. European CMOS foundries are now committed to the 'More-than-Moore' approach, and nanophotonics will become a significant part of it.

The industrial ecosystem created would include:

- R&D centers
- Component/raw material suppliers - for example, SOITEC, IQE, III-V Labs, etc.
- Equipment manufacturers - for example, SET, EVG, Suss Microtec, ASML, Aixtron, Ficon TEC, Nanosystec, Agilent, etc.
- Design tool vendors - for example, PhoeniX, Mentor Graphics, Dolphin Integration, ARM, Photon Design, etc.
- CMOS manufacturers - for example, ST Microelectronics, ALTIS, LFoundry, GlobalFoundries, etc.
- Integrators and fabless IC players - for example, ST, 3S Photonics, Oclaro, DAS Photnonics, Caliopa, Finisar, etc.
- End-users - for example, Intel, HP, Bull, Tyco, IBM, Alcatel-Lucent, Thales, FCI, Radiall, Ericsson, Nokia, etc.

Major photonic research and innovation challenges

Significant progress has been achieved in the development of Si-photonic passive and hybrid Si/III-V nanophotonic components, both passive and active. However, it has become increasingly clear that pure Si-photonic approaches cannot provide all the required functionalities. The Si-photonic waveguide size is limited by diffraction and to overcome this and so achieve viable low-power active functionalities, it will be necessary to move to nanophotonics and integrate plasmonics, metamaterials and other new materials, such as graphene, with Si-photonics.

The stakeholders from academia, applied research photonics, microelectronics foundries, and large industrial companies must work together. The competencies needed should cover silicon photonics, nonlinear optics, plasmonics, metamaterials, graphene photonics, microelectronic design, computer system architecture, and optical networks.

Medium- and short-distance datacomm systems are already starting to use silicon photonic circuits, but many challenges are still to be addressed, including:

- *Multicore processors* - the increase in performance of modern microprocessors comes through the increase in the number of cores put together in one package. However, the volume of the information transmitted by signal buses between the cores increases supra-linearly with the number of cores, and is now dictating the overall performance of the microprocessor and consumes a major part of its overall power. Electronic solutions have reached their performance limits, and the next generation systems will use optical routing of the data between chips, providing better speed, lower power consumption, and smaller footprint. The ultimate solution would be an optically transparent intra-package optical bus with all-optical processing/routing of the data between multiple microprocessing cores.

- *Network power* - networks now represent a significant part of the world's energy consumption. Though the networks use optics for information transmission, most of the power consumption lies within the electronic routing nodes. Again, optically transparent, all-optical routing combined with nanophotonics-enabled 3R should increase speed and reduce power dissipation of the routers significantly.

Both of these challenges could be solved using nanophotonics, which allows the concentration of light in small volumes, increasing the efficiency of light-matter interactions, and thus allowing non-linear, all-optical nonlinear signal processing.

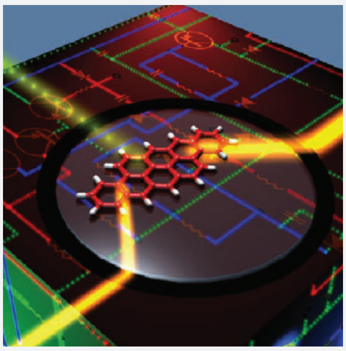

Fig 6
A single-molecule optical transistor
Courtesy of MPI Science for Light

Roadmap for 2014 - 2020

The roadmap builds on current state-of-the-art and knowledge of optical networks, silicon photonics and short-range datacomm applications.

	2014/2015	2016/2017	2018/2019	2020
Critical path from science to market	Optical I/O interfaces on chips	CMOS compatible optical network on interposer chip (optically passive, optically non-transparent)	Demonstrator of Nanophotonics-enabled 3R components	CMOS-compatible (optically transparent) all-optical network on interposer chip
Technological challenges	Technological merging of nanophotonics with CMOS micro-nano-fab (including plasmonics, graphene, non-linear materials, etc)			→
Research actions	Bring together the stakeholders from academy, applied research photonic, microelectronics foundries, and large industrial companies. The competencies needed cover silicon photonics, nonlinear optics, plasmonics, metamaterials, graphene photonics, microelectronic design, computer system architecture, optical networks			→
Innovation requirements	See the line on "research actions" Provide access to European 'More-than-Moore' CMOS foundries			→
Cross-cutting KET issues	Tight links with nanotechnology KET and with micro-nano-electronics KET			→

Expected impact for Europe

Major societal challenges will be tackled using nanophotonics for optical communications and all-optical signal processing and nanophotonic PICs for sensing applications. The development of nanophotonics will benefit the full economic chain in Europe, from fabless design companies, to 'More-than-Moore' CMOS foundries, and to network/dataprocessing equipment manufacturers.

6. Chemical / Biosensors

Main socio-economic challenges addressed

Health, demographic change and well-being - nanophotonics sensors for high-throughput drugs screening, personalized medicine, continuous environmental monitoring to provide high sensitivity, specificity, dynamic range, and integration into simple and affordable devices. Low-cost, miniaturized sensors functionalized for biosensing to move diagnostics from the lab to the point of care, allowing rapid and reliable screening. Use of nanophotonic structures overcoming diffraction limits to both enhance the fluorescence brightness per emitter and reduce the required sample volume, greatly simplifying the optical alignment for multi-color cross-correlation analysis and improving signal-to-noise (S/N) ratios, and thereby offering a potential 1000-fold reduction in measurement times.

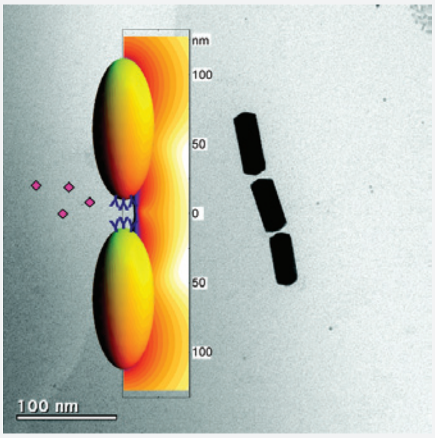

Fig 7
Nanophotonic Biosensor
source: www.bioplasmonics.ethz.ch

Food security, sustainable agriculture, marine and maritime research, and the bio-economy - nanostructured SERS substrate for providing efficient detection of food contaminants, plasmonic nanostructures for the identification and removal of water pollutants & pathogens.

Climate action, resource efficiency and raw materials - novel approaches to materials, readout and miniaturization to produce sensor elements that are disposable (low-cost) or reusable (by reconditioning surface functionalisation).

Inclusive, innovative and secure societies - remote sensing and the construction of extended sensor networks, with integrated-optic chemical sensors exploiting the expertise developed for optical communication and signal processing. Sensing in harsh environments.

Major photonics needs

The highly confined electromagnetic fields and localized plasmon resonances (LPRs) of metallic nanostructures acting as nanoantennas or other nanophotonic approaches to achieve high confinement of light can be used to detect analyte atoms and molecules in their immediate vicinity. Tuning the shape and size of metallic nanostructures can place the plasmon resonance at almost arbitrary wavelengths within the UV-IR spectral range, thus making this technique a widely applicable approach.

Three possible nanophotonic-enhanced detection mechanisms are identified:

- Monitor the position or linewidth of LPRs or other nanoscale optical resonators, which are extremely sensitive to the change of the index of refraction of the material surrounding the nanostructure
- Monitor modifications in the sensor's plasmon resonances resulting from tiny changes in distances among individual nanostructures
- Exploit the enhancement of the absorption, emission, and Raman scattering cross section of analytes in the strong local fields of plasmonic nanoantennas

In each case, significant benefits arise from the orders of magnitude increase in detection sensitivity and the nanometer-dimension spatial selectivity.

Involvement of value chain partners

A highly interdisciplinary approach will be required to fully exploit these sensor advantages.

- High-end micro/nanofabrication facilities for the nanostructures and their integration onto user-friendly and smart chips
- Sophisticated computer simulations for the electromagnetic modelling of complex shaped metallic structures for sensor geometry design
- Surface functionalization to achieve the required biological, physical and chemical interactions, and for analyte binding to the sensor nanostructures
- Microfluidic solutions for the efficient and compact handling of analytes and realization of novel single-particle readout schemes
- Ultrahigh resolution optical microscopy and spectroscopy for measurements of sensor optical properties at the single molecule level

Biotechnology industry: companies to develop nanophotonic-compatible assays and market nanophotonics to the life sciences - for example, Cytoo, Genewave, Partec, etc.
Sensor industry: development of novel optical sensors and SERS substrates - for example, Biacore, Reichert, Horiba, Renishaw Diagnostics, etc.

Pharmaceutical industries: primarily for providing support of long-term nanophotonics research projects - for example, KGF

Academic and research centres: establish partnerships with biologists and chemists for developing direct interaction with the nanophotonics community.

Major photonics research & innovation challenges

Developing nanophotonic concepts to extend the applicability and versatility of e.g. surface plasmon resonances (SPRs), achieving sensor platforms with higher sensitivity and specificity, capable of miniaturization and multi-sensor integration. By localizing the optical resonance using nanostructures, the need for sophisticated stabilization is avoided, facilitating integration and so reducing costs & sensing volumes. Nano-antennas could provide strong field enhancements, thus increasing the sensor sensitivity, though requiring some adaptation of the measurement geometry for sensor optimization.

In addition to classical modelling of the surface electromagnetic fields in the presence of extreme boundary conditions, consideration of the molecular interactions in the vicinity of plasmonic structures requires new models to analyse quantum mechanical interactions. Although not yet fully understood, single molecule sensitivity has been reported using plasmon resonance enhanced Raman spectroscopy, and offers an exciting route for full analyte identification.

Developing effective techniques for nano-structuring suitable for low cost mass production will be critical. These range from the conventional optical & e-beam lithography and focused ion beam milling, through to techniques based on self-organization, stamping, and colloidal lithography. Compatibility and integration with other key functionalities such as microfluidics will be important requirements.

A major challenge for high-sensitivity sensor design is to achieve a response specific to the analyte in question, typically requiring functionalisation of the sensor surface in order to suppress interactions of all molecules other than the analyte of interest. Adapting this to single-molecule detection will be a major challenge, with one possible route being the use of molecular monolayers suitable for use with nano-antennas.

Roadmap for 2014 - 2020

	2014/2015	2016/2017	2018/2019	2020
Critical path from science to market	Novel concepts and approaches for components and systems for sensing	Realization, characterization and demonstration of novel components for sensing	System design, integration and verification	Demonstration and application of complete sensing system solutions
Technological challenges	Confer binding selectivity to regions where the device has high sensitivity, while blocking adsorption of other local molecules	Reproducibility and usability of the nanophotonic sensor	High specificity and spatial resolution to result in short transit time and limited signal sensitivity	Assay system with parallel readout fluidic channels to create mux for throughput increase and to simultaneously distinguish multi analytes
Research actions	Functionalization of nanostructures with binding sites to make them selective to the target specimen	Invest in novel fabrication methods, e.g. nanoparticles obtained by laser ablation or nanocages obtained by chemical reduction, as an alternative to toxic gold nanorods	Develop cost-effective methods capable of seeing stationary single bio-chemical entities even in the absence of fluorescence	Combine simple and efficient detection techniques with microfluidic structures
Innovation requirements	Develop thin (monomolecular) coatings for the functionalization of nanometer-size structures	Control geometrical features with the required accuracy (could be nm for high-end applications)	Replace expensive microscope objectives with cheap optics for excitation and readout	Compatibility between optic and microfluidic technology for system integration
Cross-cutting KET issues	Surface chemistry	Nanochemistry and nanofabrication		Micro- and nano-fluidics

Expected impact for Europe

Nanotechnology in the health and personal care market has an estimated worth of €535 billion and is growing at 7-9% per annum[1]. Patents and scientific papers have grown exponentially in this sector over the last two decades, with Europe being the leading region in the number of filings. Bio-nanotechnology is an area where Europe has a relative position of strength, but it is also an area of rapid growth where further investment and research is crucial to future success and securing substantial market share.

Advanced biochemical sensors based on nanotechnology will be essential for life sciences and environmental studies, and will have huge potential for integration and the development of cheap and reliable point-of-care biosensors. Bio-nanotechnology links the areas of nanophotonics, sensing, & fluidics research, each the subject of tremendous recent development. Creating proprietary technology of benefit to European companies will ensure that knowledge in these sectors is created for and owned by European companies, and that skilled workers are educated in its development and use. Fostering and education of new researchers in this area is of high significance to the European industry.

1. “Intellectual Property in the Nanotechnology Economy” (2007), Nanoforum Network

7. Plasmon-Enhanced Magnetic Storage

Main socio-economic challenges addressed

With today's hard disk industry producing 600 million hard disks per year and each drive being composed on average of 3.5 heads, the projected number of Heat Assisted Magnetic Recording based heads is expected to reach about 2 billion by 2018. This requirement will exceed the world's current capacity for laser diodes production. If Europe becomes a major contributor for providing the technology building blocks for this market, it would provide a major boost and result in the transformation of the photonics industry, as well as securing the future of storage needs for the EU. Supporting this required volume ramp up aligns well with the program for factories of the future.

Inclusive innovation and secure society - through better data storage, better supercomputers and datacenters

Reliable, clean and efficient energy - through reductions in manufacturing energy consumption of data storage, supercomputers, and datacenter systems.

Major photonics needs

The hard disk drive (HDD) industry is facing a major challenge to continue providing increased areal density, driven by the ever increasing data storage requirements resulting from the rapid growth of social media, data centres, cloud computing, and high definition videos. Technological limitations mean that the current annual growth rate of areal density is not sustainable. Staying on the areal density growth curve is crucial for the cost structure of data storage. Indeed, unless areal density can be increased, the anticipated 40% annual increase in storage demand could only be satisfied by a corresponding increase of hard drive production. This would require huge capital investments for the HDD industry, which in turn would result in an explosion of the cost of storage. Nanophotonics offers the means for increasing the storage capacity of memory disks. The current Perpendicular Magnetic Recording (PMR) technology is expected to limit at a data storage density of $1Tb/in^2$ Hence alternative disruptive technologies must be developed to provide further increases in areal density, and so breaking through this $1Tb/in^2$ barrier.

The fundamental approach to increasing areal storage density is to reduce the size of the magnetic domains below 7nm, but this requires switching fields beyond the maximum flux density of known materials. This leads to a compromise between stable magnetic materials that cannot easily be written on, and materials that can be written on but are not stable. One approach for using high coercive field magnetic materials (i.e. offering both write-ability and stability) is to locally heat the medium temporarily, thereby lowering the switching field of the high-anisotropy, small-grain media. This approach is called Heat Assisted Magnetic Recording (HAMR)[2]. After the media is written, it cools rapidly (~1ns), thereby achieving long-term storage. However, as the required size of the region to be heated is well below the optical diffraction limit, such a writer must use a near-field device, such as a nanophotonic antenna with size and shape optimized for creation of surface plasmons[2 3] to overcome this. The intense near-field pattern is excited by appropriate laser radiation, causing a localized heating of a disk surface held in close proximity. In March 2012, HAMR was used at Seagate to demonstrate that $1Tb/in^2$ could be achieved[4], while more recently TDK demonstrated $1.5Tb/in^2$ [(5)]. With the technology advantages now proven, the first commercial storage drives using HAMR should be deployed in the 2014-2016 timeframe.

2. Challener et al., Nature Photonics, vol. 3, (2009)
3. D. O' Connor and A. Zayats, Nature Nanotech., 5, 482 (2010)
4. http://www.xbitlabs.com/news/storage/display/20120319152111_Seagate_Reaches_1Tb_Per_Square_Inch_Milestone_In_Hard_Drive_Storage.html
5. http://techon.nikkeibp.co.jp/english/NEWS_EN/20121002/243229/?SS=imgview_e&FD=46728356&ad_q

To secure this advance, the photonics industry must provide the two crucial building blocks for this technology: a suitable laser source and a plasmonic antenna to couple light into the magnetic material. Additionally, the laser radiation itself also needs to be coupled into the antenna in a reproducible, low cost, manufacturable way.

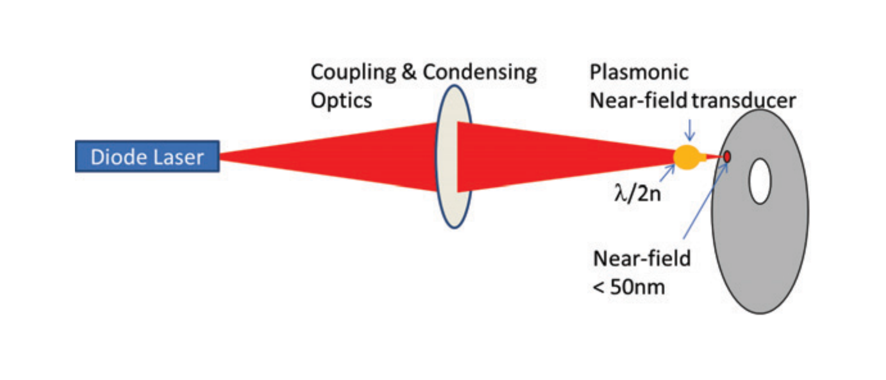

Fig 8
Schematic of HAMR scheme. The laser, optics and plasmonic near-field transducer combined in an integrated HDD write head.
Courtesy of CSEM

Expected impact for Europe

The industrial ecosystem created would include:

- R&D centres
- Component/raw material suppliers - for example, BASF, Clariant, Umicore, Show Denko, etc.
- Laser manufacturers - for example, Oclaro, OSRAM, JDSU, Sony, Panasonic, etc.
- Storage device manufacturers - for example, Seagate, Western Digital, TDK, Toshiba, etc.
- Test equipment manufacturers - for example, Singulus, Unaxis, STEAG, Audiodev, etc

It is evident that Europe has significant strengths throughout the full value chain for this industry, for example, Seagate in UK and Ireland ships some 300 million read-write heads each year, and Oclaro in Switzerland and UK has shipped more than 100 million VCSEL units. With such depth of expertise available, Europe is ideally positioned to exploit and benefit from this new technology.

Major photonics research & innovation challenges

In order to ensure the continuous growth of economically viable storage device technology, the photonics community must address two major challenges:

1. The coupling of the light into the near-field antenna in a reliable, low-cost manufacturable way.
   An attractive approach to this challenge would be to develop laser sources integrated with plasmonic antennas to reduce the size and costs of the HAMR heads. Even if the near field transducers are not integrated on the laser diodes, advances in the spatial mode profile engineering of laser diodes would help improve coupling efficiencies. Additionally, overall power dissipation will be an issue, so the lasers used will have to achieve high wall plug efficiencies (>50%) at operating temperatures up to 85°C. Additionally the development of reliable, high performance laser diode sources emitting in TM polarization would allow considerable simplification of the coupling scheme into the waveguides and plasmonic antennas. High power single mode vertical cavity surface emitting lasers are strong candidates to play a significant role in second-generation HAMR devices.

2. Design manufacturable near-field antennas that can withstand the local power density.
   The tiny area, in which the energy must be concentrated in a semi-permanent manner, means that any absorptive loss may cause the antenna to melt or deform. This can be overcome by improvements in design of the antennas or by using more robust materials. Unfortunately there is a trade-off between robustness and loss, and optimizing this balance will be a key objective.

Beyond HAMR, it is expected that there will be a need to identify and produce even higher-density patterned media, with a track pitch similar to the width of the plasmonic antenna tip itself. Superior higher-anisotropy materials, such as FePt, could provide a route for this, offering further increases in data density.

Roadmap for 2014 - 2020

	2014/2015	2016/2017	2018/2019	2020
Critical path from science to market		High yield coupling scheme laser sources into plasmonic structures Very large scale production of laser diodes Large scale production of plasmonic antennas Production of new magnetic materials for disk material	Manufacturing ramp	Manufacturing ramp 2nd generation of HDDs with laser diodes integrated with plasmonic antennas Very large scale production of low cost lasers integrated with plasmonic

Roadmap for 2014 - 2020

	2014/2015	2016/2017	2018/2019	2020
Technological challenges	Light delivery to magnetic material High Hc magnetic material Tailored optical field in laser diodes Vertical emission laser diodes TM polarization control laser diodes	Light delivery to magnetic material High Hc magnetic material Power robust near field transducers Tailored optical field in laser diodes Power robust near-field transducers	Design of HDD heads with vertical emission, beam controlled laser diodes and plasmonic structures	
Research actions	New material system for laser diodes Magnetic materials with high Hc and fast cooling and good heat conductivity Antenna shape Metal used for transducer In-coupling scheme in antenna	Design of second generation antenna Co-design of laser diode source with plasmonic antenna Reliable lasers with integrated plasmonic Magnetic materials with high Hc and fast cooling and good heat conductivity	Design of second generation antennas Reliable lasers with integrated plasmonic	Reliable lasers with integrated plasmonic
Innovation requirements	Low loss, high local field, efficient transducers	Integration of laser diode source with plasmonic antenna	HDD head design to use integrated laser diode with plasmonic	
Cross-cutting KET issues	Tight links with KETs involved with nanotechnology, data storage, micro-nano-electronics and manufacturing			→

Expected impact for Europe

The production volume for Hard Disks is significantly larger than that of CD and DVD players. According to iSuppli, the worldwide revenue for computer-related hard disks was approximately 28B$ in 2010 vs. a revenue of around 15B$ for computer-oriented optical disk drives. Moreover, the current trend is that optical disk drive production is declining due to the success of tablets and ultrabooks in detriment of laptops, while the demand for hard disks remains constant or increases. The projected production volume of the photonics components, e.g. lasers, coupling optics and near-field transducers, required to service HAMR technology will exceed that of the CD, DVD & BluRay industries combined.

Addressing the quantity of HAMR heads required by the HDD industry will transform the photonics industry into a mass market, and Europe will greatly benefit from this transformation.

Conclusions & Recommendations

- Research in nanophotonics is actively addressing potential applications across a wide range of subjects, but the connection to European industry is still relatively weak. If these connections can be made, European industry is in a strong position to exploit nanophotonics and deliver novel technological solutions.

- To ensure appropriate representation of this potentially disruptive technology within Horizon 2020, the nanophotonics community needs to interact effectively with the Photonics21 working groups and so have a direct influence on the definition of the PPP roadmaps.

- Nanophotonics bridges two KETs - photonics & nanotechnology. This widens the range of accessible funding sources and allows strong and desirable cross-KET cutting activities to be exploited.

- Targeted support is required to address:

    - Fundamental research in the underlying physics of nanophotonic interactions

    - Cost-efficient nanofabrication and nanopatterning methods with sub-nanometre dimensional control

    - Development and optimization of application-specific photonics devices and systems

- Support for curiosity-driven research is also essential, and funding mechanisms should allow for the unexpected.

- The enabling nature of nanophotonics will be best exploited through the establishment of infrastructures to allow the free flow of information between researchers and potential users of the technology, and to facilitate access to state-of-the-art fabrication technologies.

- Education and training will be essential for building a strong and productive nanophotonics community. This should be provided through specialist academic courses for graduate and post-graduate students.

- Primary and secondary level education providers would benefit from focussed photonics outreach activities from universities, industry and regional clusters.

- Photovoltaics does not currently fall within the Photonics sector, so alternative agencies, such as Energy, must be solicited to secure support.

Workshop Participants

King's College, London
10 - 11 July, 2012

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