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Future horizons for photonics research 2030 and beyond

PHOTONICS LEADERSHIP GROUP

FUTURE PHOTONICS HUB

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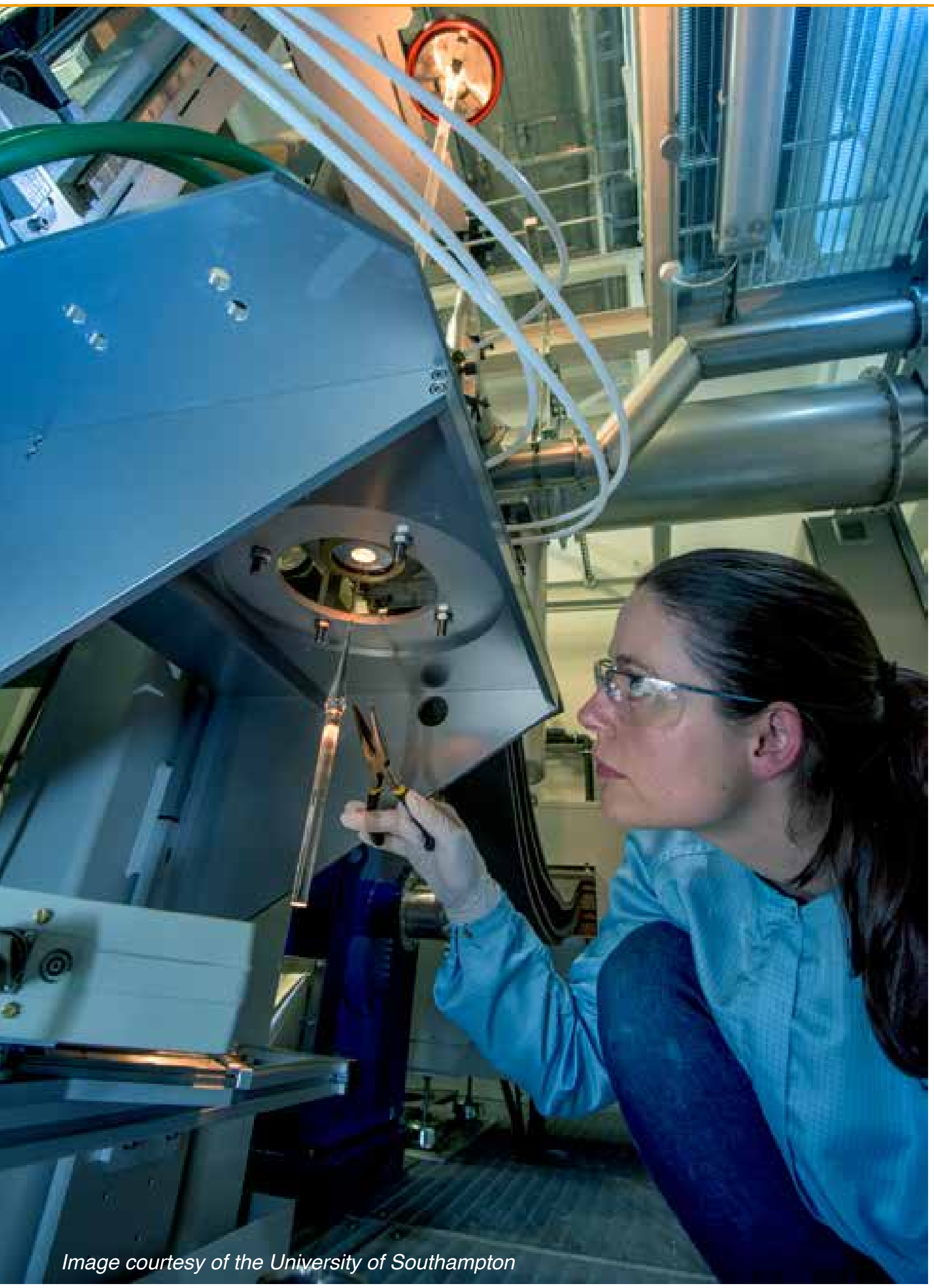


Image courtesy of the University of Southampton

For decades, the UK photonics industry has been at the forefront of global innovation and research excellence. Recent developments, such as the advanced LIDAR systems for autonomous vehicles, secure quantum computers and 5G communications, ensure that photonics continues to be a vitally important sector with potential for major growth across multiple technologies.

As a massive £13.5 billion industry, the photonics footprint is evident in every part of the UK. This footprint must be properly recognised and supported by governments.

This report, which draws on expertise from leading academics and the Photonics Leadership Group, identifies the considerable opportunities for UK photonics and calls for a multifaceted approach from researchers, industry leaders and policy-makers in order to maximise economic and societal benefits.

Supporting the continued growth requires investment in people and facilities. The 21st century is the century of light. Let's ensure that the people and nations of the UK remain in the vanguard of photonics.

Carol Monaghan, MP, chair of the All-Party Parliamentary Group on Photonics and Quantum

Published: September 2020

Executive summary

Future horizons for photonics research, 2030 and beyond

Photonics enables over $2 trillion worth of global markets for a vast range of products. Many of the goods and services we use every day rely on photonics - from communications networks to tools used in manufacturing on a vast industrial scale.

The demand for photonics innovation is growing as society becomes ever more connected, digital, safety conscious and environmentally aware. Designers, manufacturers and photonics users are continually searching for new breakthroughs which will help give their products the competitive edge.

This report looks a decade and more into the future and aims to distinguish what will be possible in photonics, the disruptive technologies on the horizon and the opportunities that they present for the UK to lead in knowledge generation and wealth creation.

It presents the collective vision of 26 of the UK's leading photonics academics, representing 20 UK institutions and with a combined research income of over £650 million. These eminent figures in the photonics community were invited to participate in a horizon scanning exercise led by the Photonics Leadership Group (PLG), a voluntary association of senior leaders in industries and research organisations active in photonics.

The purpose of the report is to stimulate engagement from government, funding agencies and industry to shape and support future innovation strategy, and to mobilise the next generation of researchers, who ultimately will be the ones to turn these concepts into reality.

The report concludes that realising its vision will accelerate the UK's existing £13.5 billion photonics industry and support future growth across the economy, in all industry sectors due to their widespread dependence on photonics technologies.

The report makes seven recommendations for action:

1. UK academics should transform the 70 ambitious topics on the photonics horizon into world leading research activity.
2. Research agencies should fund photonics research, investing in people, facilities and capability across the UK.
3. Researchers and funding agencies should strive for balance between materials, processes and systems innovation, leveraging their interdependency.
4. Policy makers are encouraged to support disruptive photonics research with impact on multiple societal challenges and markets.
5. Stakeholders should merge this research vision with industry demand and government policy.
6. Industrial Strategy Challenge Fund (ISCF) Directors should integrate these horizon scan findings with vertical market roadmaps.
7. The UK photonics community should champion this vision of the future of photonics to the world.

This report defines the vision for the future direction of photonics in 70 ambitious research topics. These include disruptive innovations in established areas of study and new, emerging research fields, such as biodegradable, low carbon and brain-inspired photonics.

What is photonics?

Photonics is the science of light. It is the technology of generating, transmitting, manipulating and detecting visible and invisible light. Photonics can be seen as the 'optical equivalent' of electronics and includes lasers, cameras, LEDs, fibre optics, displays, solar cells and much more.

The research topics are organised into four broad categories: **materials, optical and physical phenomena, manufacturing processes and devices, and systems.** These are set in the context of nine, 'great challenges' representing major societal trends and concerns which will influence and motivate future photonics innovation: **data, health and ageing, physical pollution, mobility and transport, climate change, defence and security, economic patriotism, scale and food production photon.**

The world is demanding ever more photonics innovation to enable next-generation capability in a huge range of markets from farming to healthcare and defence. Unlocking the full economic impact of photonics for the UK will depend on responses to the recommendations of this report and a collective ambition to be a world leader in innovative solutions to global challenges, leveraging the very best enabling technology.

Key:
Colours indicate the strength of the impact of each research topic on the upcoming 'great challenges'

Highest, broadest impact

Significant, focused impact

Materials

- 2d materials & hetrostructures for photonics
- Optimised (AI) design of next generation photonic materials
- Reconfigurable adaptive & programmable photonic materials
- Direct bandgap silicon & new silicon photonic materials
- Low threshold power non-linear materials
- Materials for >100 GHz optical modulators & sub ps switching
- Biocompatible photonic material
- Efficient phase change materials
- Electrochemically stable materials for solar-hydrogen
- Expanded spectral capability of materials in UV & IR
- High-speed operation organic materials
- Negative n2 materials
- Sustainable/ biodegradable photonic materials
- Very high efficiency, easily integrated single photon sources

Optical and Physical Phenomena

- New quantum phenomena at the macro-scale
- Chemistry & chemical reaction pathways controlled by light
- Compact attosecond physics
- Extreme high energy pulsed phenomena for breaking vacuum
- Focal volume manipulation
- Functional topological devices at room temperature
- Light controlling movement beyond few nm
- Light-matter interaction, control & assembly on a molecular scale
- Optical imaging of the nervous system
- Opto-mechanics for RF-microwave-THz-optical interface
- Photonic-enabled synthetic fuels & energy storage
- Precision optical measurements for testing fundamental physics
- Quantum limited detection in mid-IR
- Ultra-short temporal pulse-shaping

Future Manufacturing Processes

- Integration processes at scale (1000+ elements)
- Nanophotonic devices for on-chip optoelectronic integration
- Integrated quantum sensing, imaging, processing & communications
- Processes for integration of new functionalities with photonics
- High-volume processes for point-of-care testing
- Efficient integration of plasmonics
- Flexible optical manipulation for limited access volumes
- High-speed nm optical imaging for process control
- Integration of 2D materials
- Low energy manufacture of photonics
- Optical cell manipulation for regenerative medicine
- Processing of materials for repurposing & reuse
- Scanning probe techniques for photonic nano-material assembly
- Solar driven chemical processing
- Testing of massively complex systems at wafer scale

Devices and Systems

- Beyond CMOS integrated photonics & electronics
- Fully optical internet & required components
- Optical point-of-care diagnostics
- Neuromorphic photonics
- Coherent comms across entire RF/THz/Optical spectrum
- Deep tissue optical imaging
- Extreme high power /energy amplified laser systems
- Flexible, reconfigurable & programmable optical circuits
- Hybrid quantum & conventional communications systems
- Large-scale optical switches
- Large detector arrays at multiple wavelengths
- Miniature THz sources at room temperature
- Next generation non-mechanical lidar
- Quantum repeaters & entanglement distribution
- Quantum communications in space & at long wavelengths to THz
- Single Photon detectors for SWIR & MIR
- Sub nanometre optical imaging
- Ultra-wide bandwidth optical networks, amps, modulators & fibres
- Very high-efficiency lasers (>95%)
- Efficient & high bandwidth PV cells
- Flexible laser material processing systems with multi/ variable lasers
- High-speed, ultra high-sensitivity detectors in visible spectrum
- High-speed, low-energy, ultra-high density & secure memory
- Merging of AI & photonics sensory data (e.g. artificial noses)
- Optical memory from fast RAM to ROM
- Quantum computing at 1000's of Qubit scale
- Chip level systems in the ultra-violet

Introduction

Taking our knowledge of how we can make, use and interact with light to the next level will give us a new generation of products and services sustainably available, when and where we need them.

Almost all every day goods and services depend on photonics technologies, either to bring them into being through efficient manufacturing processes or to keep them at the cutting-edge of performance. Photonics enables mobile phones, the internet, car production and even DNA testing. The photonics industry directly employs 69,000 people in the UK and generates more than £13.5bn of economic value in products and services, of which many are exported worldwide.

As much as today's society depends on photonics, we are only at the very beginning of the optical era. A step change in photonics innovation is needed to address the global challenges of tomorrow. Pushing back the boundaries of knowledge will give rise to more new innovative products and services, for a safer, more sustainable future.

In this report, we identify the key topics that will be the focus of future photonics research ten years from now. We offer a vision for research that, if supported, will consolidate the UK's status as a global leader in photonics innovation.

Looking into the future is not an exact science. Using a horizon scanning process based on the Government Office for Science's Futures Toolkit, we have captured the ideas and insights of 26 distinguished photonics academics from leading UK institutions. Together, the participants have a combined research income of over £650 million and more than 40 prestigious awards and accolades.

The intention for this horizon scan is to begin a three step process, which aims to stimulate interaction between academia, industry, government and funding agencies engaged in research and innovation.

Here, we present Phase 1, our collective vision for future research and innovation, grouped into four broad categories: materials; optical and physical phenomena; future manufacturing processes; and devices and systems. We acknowledge that this categorisation is somewhat artificial as there is natural interconnectivity between the groups, for example new devices often require new manufacturing processes using new materials. However, the categories serve as a useful framework to organise the many ideas into overarching focal research areas.

Our horizon scanning exercise was conceived in the context of a UK government's commitment to support research and innovation, an Industrial Strategy with defined Grand Challenges and an ambition to grow UK R&D investment to 2.4% of GDP, the establishment of UK Research and Innovation (UKRI) and Brexit.

We completed the horizon scanning exercise during the coronavirus global pandemic. Participants commendably overcame the hurdles of lockdown to develop a vision looking beyond the immediate challenges of 2020 to outline a long term vision for photonics research. In focusing on the ten year horizon, we reveal a diverse and hugely significant future for photonics research in the UK.

Impact on society

In less than a single lifetime, society has become completely dependent on photonics. It is impossible to imagine modern life without the photonics innovations of the last 25 years:

Optical fibre (a UK invention) and telecommunication lasers have been harnessed to power the global internet

High power lasers for mass production, from welding lighter, safer, more efficient cars to cutting stronger mobile phone screens

Optical imaging and sensing has transformed ophthalmology, cancer and rapid diagnostics testing in healthcare

Cameras become manufacturable in millions for today's consumers

Liquid crystal and organic electronic displays (both UK inventions) have revolutionised entertainment and ways of working

This is only the start and the optical era is just beginning. In the future, we will be far more dependent on photonics with innovations delivering benefits across society:

Ultimately secure quantum communication and storage of the world's data

Agile, adaptable security and defence, leveraging the speed of light to safely and efficiently deliver capability

Decarbonisation with low impact photovoltaics, precision control of wind generation and ultra-efficient data storage and processing

Digital manufacturing for efficient local production and rapid volume scaling using 3D printing and precision process control

Deep body soft tissue imaging for precise early disease diagnosis

Real-time disease and pollution detection, building confidence in our environment and surroundings

Real-time image recognition and AI informed decision making using optically enabled superfast classical and quantum computers

Digital factories, remote working and interactive entertainment, using universal, resilient, real-time optical fibre connectivity

Autonomous vehicles and factories in common use guided by laser detection and ranging (LiDAR)

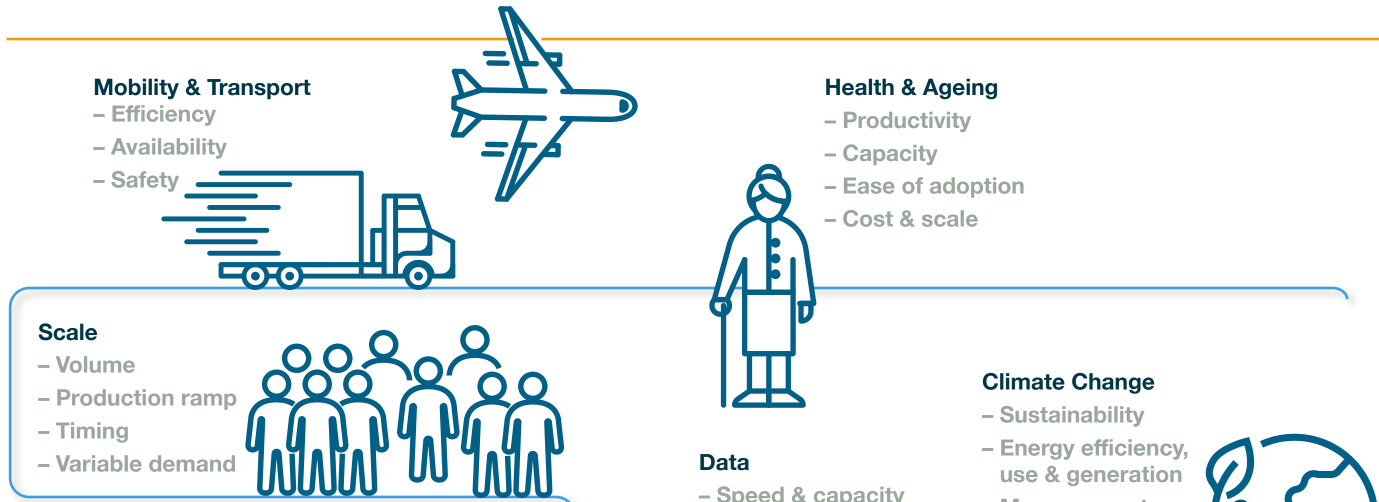
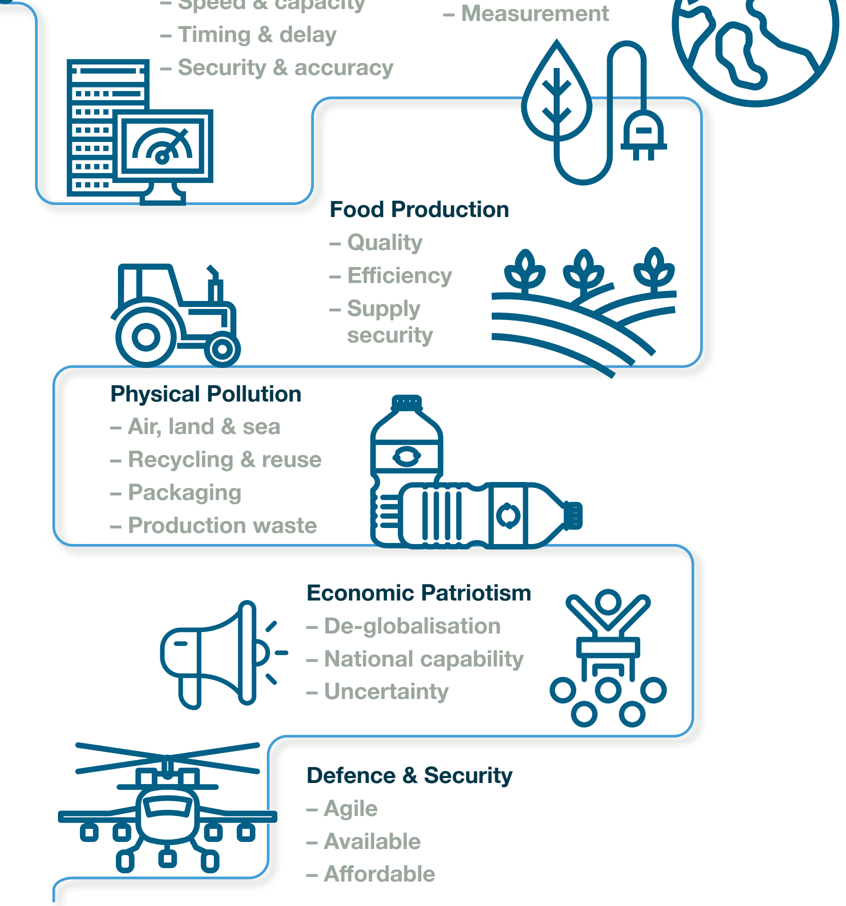
Recreating the conditions at the birth of the universe with ultra-high power lasers

Nine great challenges for photonics

Photonics innovations will be vital to tackling almost all the major challenges facing 21st century society.

Photonics is already a well-established part of advanced products and manufacturing processes around the globe. Innovations based on the capture, transmission, manipulation and use of light can often be found behind breakthrough technologies, like the systems making cars safer and more efficient and the communications networks connecting people all over the world with data, entertainment and each other. Together, photonics technologies and the applications they enable are estimated to underpin 11% of the global economy (SPIE 2020).

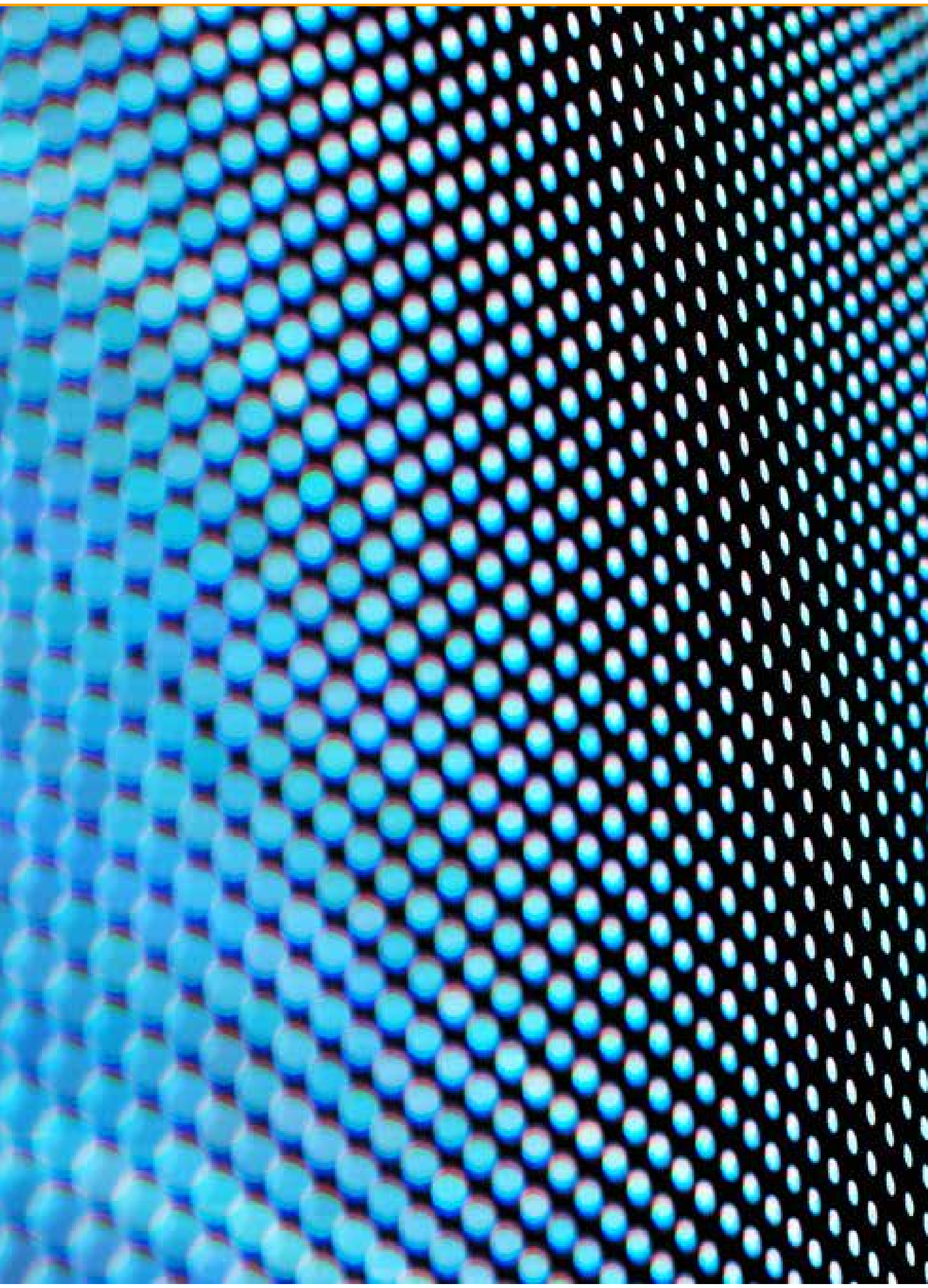
To understand the context for our future photonics horizon, we updated and globalised the four Grand Challenges identified in the 2017 UK Industrial Strategy. Through this exercise, we defined nine 'Great Challenges' for photonics. A detailed analysis of the impact of photonics on each of these challenges is outside the scope of this report, instead the challenges are recognised as key drivers and influences that will inevitably shape future photonics research possibilities.

The ubiquitous nature of light means that innovating in photonics will ensure progress against multiple challenges and maximise resilience to market disruption. For example, advances in photonics integration at high volumes for communications can also be applied to mass healthcare diagnostics and improving food production, and the sort of resilient solutions developed for defence and security applications can also be used in creating safer, more reliable autonomous vehicles.

Solutions to the Great Challenges will require complex systems which combine photonics with electronics and many other technologies. However, when a new product is developed it is often the photonics content that differentiates it from the competition. The high degree of knowledge embedded in photonics, and the globally leading position of UK photonics research and our world leading photonics manufacturing industry creates a strong UK ecosystem from which to build. We are therefore uniquely placed to push the boundaries of knowledge and transform innovation into value captured throughout the UK economy.

Materials



Innovation in materials will continue to be a key driver for photonics advancement in 2030 and beyond.

Developing advanced materials has always been at the heart of photonic innovation. Silicon technologies deliver affordable solar power, indium phosphide materials enable long distance telecommunications and gallium nitride makes efficient white light LEDs possible.

In the future, enhancing existing semiconductor, crystalline and glass materials will be essential to realising new sensing capabilities in the infrared and ultraviolet, providing secure quantum cryptographic communications and quantum imaging through **efficient single photon sources,** and potentially enabling the efficient splitting of water to produce hydrogen using sunlight.

New **2D materials are also emerging.** These build on graphene, first invented the UK, and comprise layers just a few atoms thick. At this scale, quantum confinement and surface effects produce unique optical properties. Their unique bonding properties make it possible to stack different semiconducting **2D materials into layered heterostructures,** producing complex, flexible, optoelectronic components which can be mounted on to any surface. In addition, metamaterials, made from repetitive structures smaller than the wavelength of the light, can produce optical properties not found in nature. Properties such as **large or even negative refractive indices** offer imaging at resolutions previously thought to be impossible and create the intriguing prospect of 'invisibility' cloaking.

These new materials will lend themselves to being combined with the nascent field of **integrated/ silicon photonics** where combining many components in miniature is increasing the volumes at which photonic devices can be efficiently manufactured. In the future, integrating new 2D materials into these processes will be essential to achieving the performance advances required by consumer-facing applications across the digital economy.

Historically, photonics integration has been limited as silicon cannot emit light. This is because silicon has an indirect band gap. However, new research is emerging which indicates that by mixing silicon with other materials and manipulating its crystal structure, it may be possible to produce light-emitting **silicon alloys**. This breakthrough has the potential to greatly simplify photonics integration and also to enhance the compatibility of devices that can be efficiently manufactured at scale.

The ability to optically/electrically control a material's optical properties already has many applications. However, these usually require continuous electrical power. The future will see metastable materials such as **phase change chalcogenides, enabling reconfigurable, adaptive and programmable photonics,** which can be switched and held in different states without power. Realising **lower non-linear thresholds** will also extend applications for dynamic systems. Such versatile optics, including those where light as well as electricity is used to control light, will dramatically increase system capabilities, production yield, adaptability and late stage customisation, as well as opening up new applications.

Optical modulators are vital to transforming electrical into optical signals. **Low energy, fast switching (sub-picosecond) materials, operating over a wide spectral bandwidth at low loss** will be essential for enabling optical modulators operating at over 100 GHz and supporting system capability at ever higher data capacities.

To date, the development of photonic materials has relied solely on the expertise of world-leading scientists. Computer learning and AI has the potential to augment human intuition, leading to **next-generation photonic materials with optimised functionality.** This will be a powerful tool for developing **biocompatible photonics** for medical applications and **sustainable / biodegradable photonic materials** to support transitioning to a greener digital economy.

"For me, this process has really emphasised the breadth of photonics-based research and how the far-reaching impact of this research will continue to expand and diversify"

Dr Natalie Wheeler, University of Southampton

Optical and physical phenomena

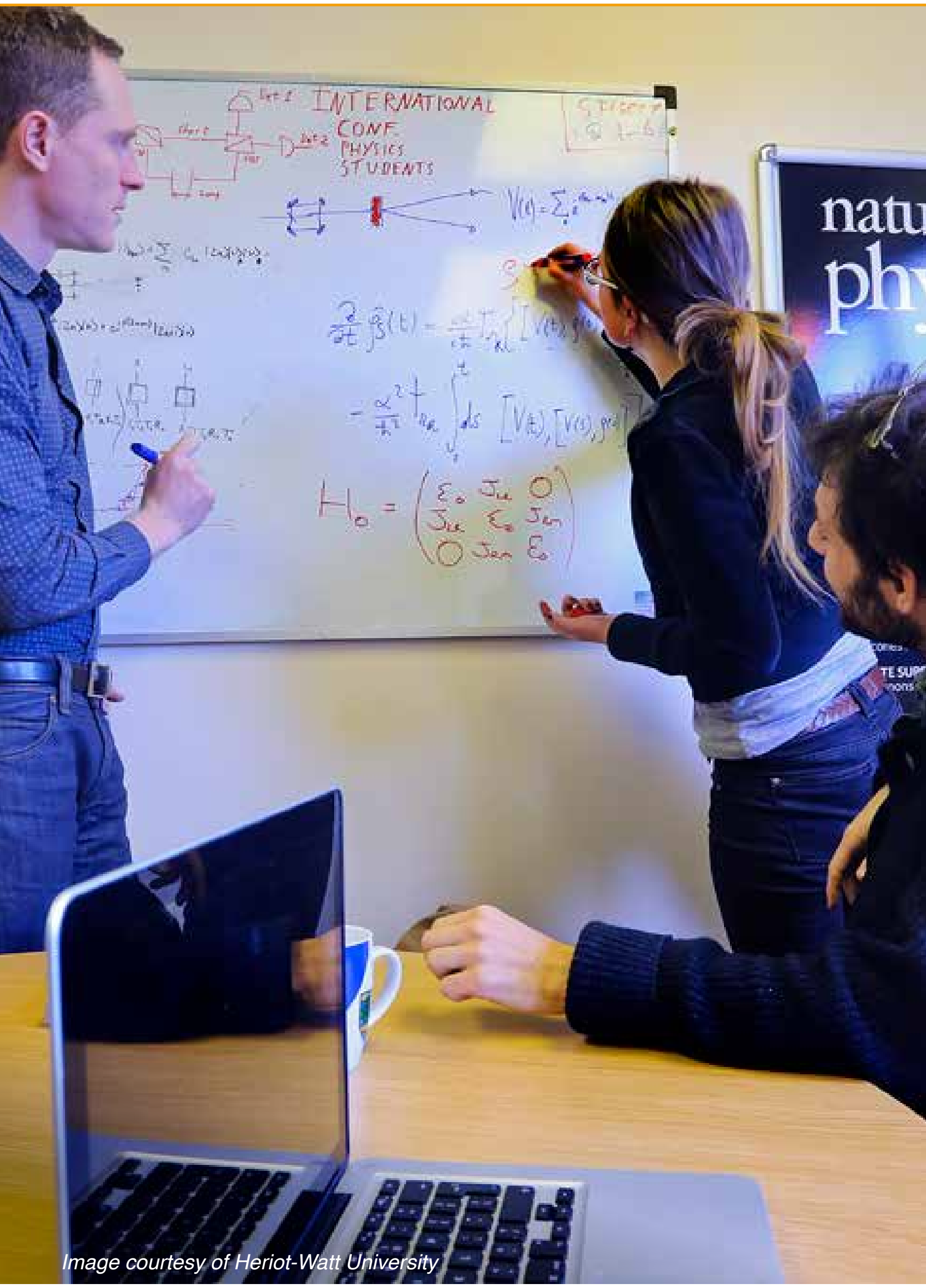


Image courtesy of Heriot-Watt University

If advances in materials are to be linked with future manufacturing processes and device development, it is fundamental to understand interactions between light and matter.

Attosecond science has been in existence for some 20 years and has lifted the veil on molecular structure at sub-atomic spatial and temporal resolution. Continued developments in this field, such as **ultra-short temporal pulse shaping** will enable **precision optical measurements for testing fundamental physics.** This will further our understanding of light-matter interactions for applications in data storage, materials processing and energy efficiency.

Ultra-high power pulsed lasers (beyond 100 petawatt), will support new **extreme high-energy pulsed phenomena** enabling exploration of new domains in high-energy and particle physics and potentially enabling breaking of vacuum. It will be possible to test predictions of quantum electrodynamic theory which emerged ~100 years ago, opening up new areas of physics research and advancing humankind's fundamental understanding of the universe.

Efforts to take **attosecond physics** technologies and condense them into **compact, benchtop, systems** will bring these capabilities out of large, national research facilities into localised research labs and facilitate applications in e.g. medical imaging and perhaps even treating spent nuclear fuel.

Optical and physical phenomena

New quantum phenomena at the macro-scale	Chemistry & chemical reaction pathways controlled by light	Compact attosecond physics	Extreme high energy pulsed phenomena for breaking vacuum	Focal volume manipulation
Functional topological devices at room temperature	Light controlling movement beyond few nm	Light-matter interaction, control & assembly on a molecular scale	Optical imaging of the nervous system	Opto-mechanics for RF-microwave-THz-optical interface
Photonic-enabled synthetic fuels & energy storage	Precision optical measurements for testing fundamental physics	Quantum limited detection in mid-IR	Ultra-short temporal pulse-shaping	

Beyond source development, the exquisite control of light-matter interactions will open up new frontiers in optical processing and devices. The 2D techniques currently available for shaping light are limited to beam profile control in the focal plane. However, full 3D **focal volume manipulation** is needed to advance non-linear processes and for applications with ultra-strict tolerances, such as surgery, **optical imaging of the nervous system** and ultra-short pulse material processing, such as glass welding, waveguide inscription etc. Designing materials for **functional topological devices at room temperature**, which exhibit precisely engineered interactions with photons, could also enable advances in ultra-fast imaging and photodetectors.

Interest in the mid-infrared spectral region is growing rapidly because of the unique signatures of pollutants which can be identified at these wavelengths. **Mid-infrared quantum limited detection** could be exploited for ultra-high sensitivity sensors, e.g. for point-of-care medical diagnostics, advanced imaging and security applications.

Harnessing the spatial and temporal resolution of light for precision control of matter is also on the horizon. Using **light to control movement beyond a few nanometres** will enable biophotonics applications, for example in medical procedures. Exploiting **light-matter interaction for control and assembly on a molecular scale** could lead to a new generation of dynamic optical components or a novel conveyor belt in device production.

New **interfaces between radiofrequency, microwave, terahertz and optical domains** are needed to bridge between different frequency regimes. With ultra-low noise characteristics, such interfaces could act as a quantum compatible link between electronic signals and free-flying optical information enabling secure communication between quantum computers. **New quantum phenomena at the macro-scale** could be essential to the practical application of many quantum 2.0 phenomena which leverage the superposition of states.

Chemistry and chemical reaction pathways controlled by light offer a means by which to meet the growing need for more efficient food production and synthetic chemistry. Using light to switch on, modify or control chemical reactions could realise **photonics-enabled synthetic fuels and energy storage** and prove critical to addressing the challenge of clean growth.

"The visions crystallised by the horizon scanning exercise are an inspirational call to arms for young photonics researchers across the country"

Dr Robert Richards, University of Sheffield

Future manufacturing processes

Image courtesy of the University of Sheffield

Novel processes are the critical bridge connecting materials and functional phenomena to useful devices and systems.

Future photonics manufacturing processes involve a series of chemical, physical and/or mechanical operations which change, combine and enhance material properties.

Researching new photonics manufacturing processes involves focusing on a combination of one or more key elements:

- **Resources** e.g. the efficient use of energy and/or materials consumed
- **Scale and repeatability** e.g. producing a given volume at high yield
- **Novel outputs,** often through enabling new combinations of different materials
- **Compatibility,** with other photonic and non-photonic components, processes and systems

Enabling integration, where multiple functional elements are combined together, will be a major theme in the future of photonics, providing benefits greater than the sum of individual components. This includes **integration at scale,** i.e. for high volume production, and integration of **new functionalities, quantum devices, plasmonics and 2D materials.** With the research challenges depending strongly on what is being integrated for what production volume.

Manufacturing processes

Integration processes at scale (1000+ elements)	Nanophotonic devices for on-chip optoelectronic integration	High-volume processes for point-of-care testing	Efficient integration of plasmonics	Integration of 2D materials
Integrated quantum sensing, imaging, processing & communications	Processes for integration of new functionalities with photonics	Flexible optical manipulation for limited access volumes	High-speed nm optical imaging for process control	Low energy manufacture of photonics
Optical cell manipulation for regenerative medicine	Processing of materials for repurposing & reuse	Scanning probe techniques for photonic nano-material assembly	Solar driven chemical processing	Testing of massively complex systems at wafer scale

Research in the near-infrared wavelength region used for communications will focus on photonics integrated circuits, involving **thousands of functional elements** and addressing issues such as yield, volume capacity, resource use and process compatibility. In other spectral domains and functions, integrating only tens of elements is an ambitious endeavour, and working with new materials at novel wavelengths with tight constraints on e.g. optical loss for quantum superposition applications, will be especially challenging.

Integration is, however, not easily abstracted. Rather, developing robust pathways for integration with other photonics elements and other technologies, e.g. integrated electronics, will be a key theme within many different areas of photonics research. Designing integration in at the earliest opportunity will ease the pathway to adoption reducing time-to-market and increasing impact.

Developing new processes for producing photonics at high volumes, i.e. million of devices and with high yield, often runs in parallel with integration. **Nanophotonics devices for on-chip integration, nano-material assembly, testing at wafer scale, high speed nanometre imaging** and **high volume processing for point-of-care testing** will all support volume manufacturing. They represent an ongoing trend in photonics, transitioning from a bespoke technology applied in niche applications, to a ubiquitous capability deployed on a consumer relevant scale across multiple applications.

Scalable processes will also include those supporting distributed manufacture close to point-of-use. This will require new manufacturing processes, less dependent on large scale capital equipment, that can be efficiently reproduced in multiple locations for increased flexibility, resilience and security. Combined with reconfigurable photonic devices using metastable materials, such novel processes will support greater adaptability in manufacturing, enabling more efficient new product introductions and responsive matching of capacity to demand.

Overall, economical, sustainable production methods will rise in prominence with the widespread, large-scale use of photonics. This will manifest in the **low energy manufacture of photonics** and **processing of materials for repurposing and reuse,** which directly aligns with the future focus on sustainable photonic materials.

There are also a few select new processes whose very novelty drives innovation. **Solar driven chemical processing, optical cell manipulation,** and the **manipulation of light in sub-millimetre spaces** are all examples of part process, part novel phenomenon. They give rise to novel photonic methods and generate new optical tools with applications far beyond the field of photonics.

"I'm convinced that the future will be defined by integration of an entire system on a chip. A lab or a computer on a heterogeneous chip are just the first systems we will demonstrate"

Dr Katarzyna Balakier, UCL

Devices and systems

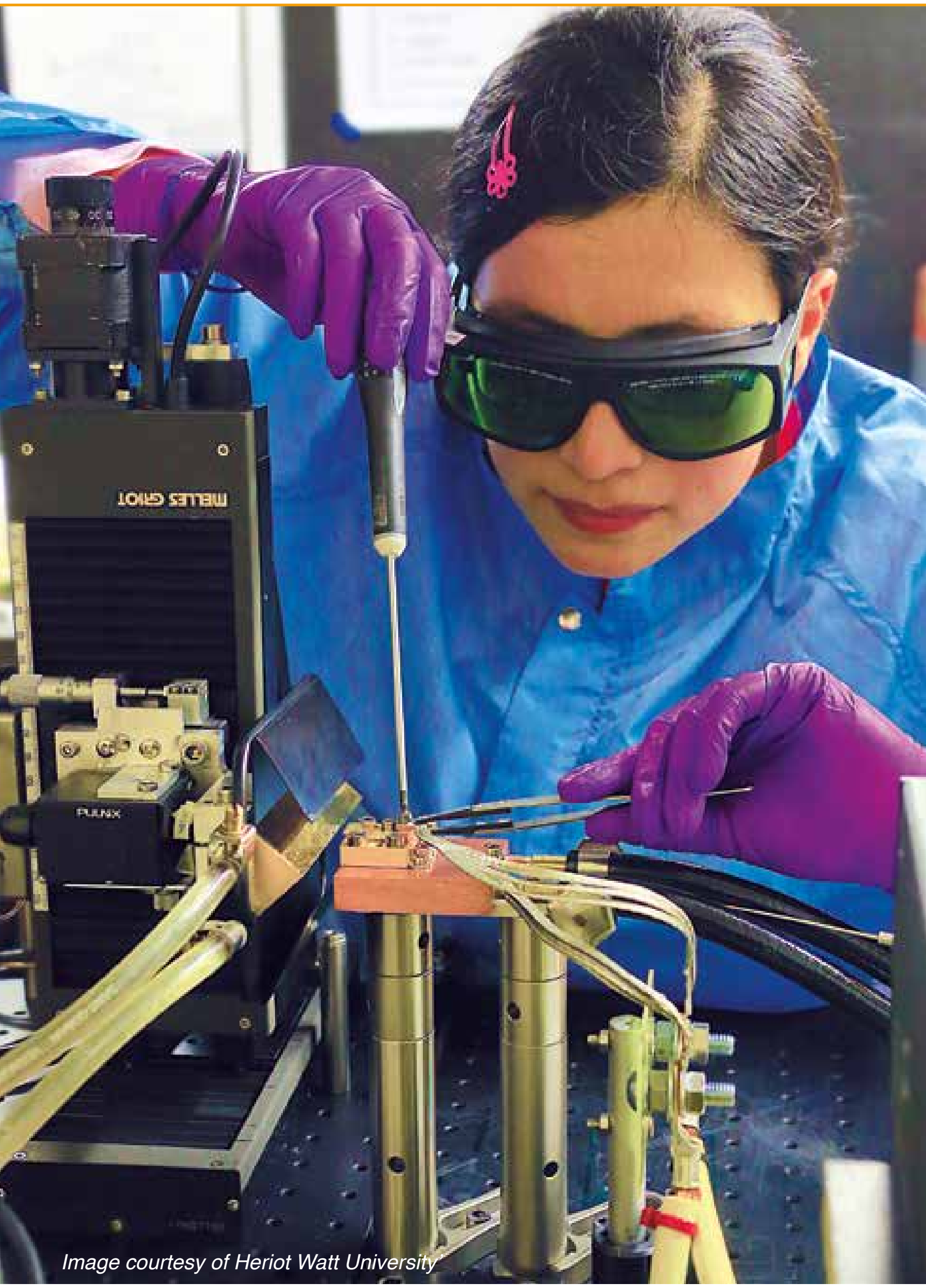


Image courtesy of Heriot Watt University

21st century challenges are driving the development of new photonic devices and systems.

Lasers are one of the most important devices in photonics. First demonstrated 60 years ago, lasers are found in everything from smartphones and the internet to aircraft navigation and precision time keeping. Lasers are essential to the manufacturing of everything from cars to medical implants, making materials processing (cutting, joining, marking) their most valuable market. The trend towards making technology more 'smart' is now driving laser innovations, balancing dedicated mass production against flexible manufacturing.

For mass production, cost-effectiveness, reliability and energy efficiency must continue to improve. There remains substantial potential for very high efficiency lasers (approaching 95%) with the associated economic and environmental benefits. We also expect new innovation in extreme high-power and high-energy lasers, including those emitting ultra-short pulses for; ultra-fine sub-micron material processing and lithography; high speed and accuracy glass and ceramics, and processing of 'difficult' materials (e.g. copper in electric vehicles); and to support new fundamental science and defence applications.

For adaptable, localised manufacturing, flexibility and broad tunability is required in laser pulse duration, shape, wavelength and repetition rate. This will require advances in broadband amplifiers, beam delivery systems and materials. On-the-fly tunability offers the potential to combine multiple material processing steps onto one workstation or to provide fully flexible job-shop capability, essential for decentralised industry 4.0 manufacturing and efficient 3D printing. These advances offer additional benefits in under-developed spectral regions, including terahertz (THz) frequencies where miniature photonics-enabled THz sources at room temperature need to be developed for 6G communications.

Devices and Systems

Beyond CMOS integrated photonics & electronics	Fully optical internet & required components	Optical point-of-care diagnostics	Next generation non-mechanical LIDAR	Quantum repeaters & entanglement distribution
Neuromorphic photonics	Coherent comms across entire RF/THz/Optical spectrum	Deep tissue optical imaging	Single photon detectors for SWIR & MIR	Sub nanometre optical imaging
Quantum communications in space & at long wavelengths to THz	Extreme high power /energy amplified laser systems	Flexible, reconfigurable & programmable optical circuits	Hybrid quantum & conventional communications systems	Very high-efficiency lasers (>95%)
Ultra-wide bandwidth optical networks, amps, modulators & fibres	Large-scale optical switches	Large detector arrays at multiple wavelengths	Miniature THz sources at room temperature	Efficient & high bandwidth PV cells
Flexible laser material processing systems with multi/variable lasers	High-speed, ultra high-sensitivity detectors in visible spectrum	High-speed, low-energy, ultra-high density & secure memory	Merging of AI & photonics sensory data (e.g. artificial noses)	Optical memory from fast RAM to ROM
Quantum computing at 1000's of Qubit scale	Chip level systems in the ultra-violet			

Photonics can play a further role in tackling climate change by increasing the efficiency of photovoltaic solar cells to harvest the sun's energy. Research will focus on improving **efficient high-bandwidth photovoltaic cells** and leverage UK capabilities in compound semiconductor materials, as well as alternative/organic photovoltaics, well-suited to incorporating into architectural design.

Photonics is closely associated with precision measurement and imaging. Healthcare and autonomy will be key drivers in sensing innovation with the use of **AI and machine learning to merge multiple sources of photonics** and other sensor data. Photonics-enabled **point-of-care diagnostics and genomic screening** will be supported with integrated photonics and new **deep tissue scanning** techniques. **Non-mechanical beam steering** and **single photon techniques will advance LIDAR systems** for autonomous vehicles. Advances in photonic sensing, including improvements in **sub-nanometre optical imaging** and **chip-level ultra violet sub-systems** will also benefit a wide range of applications.

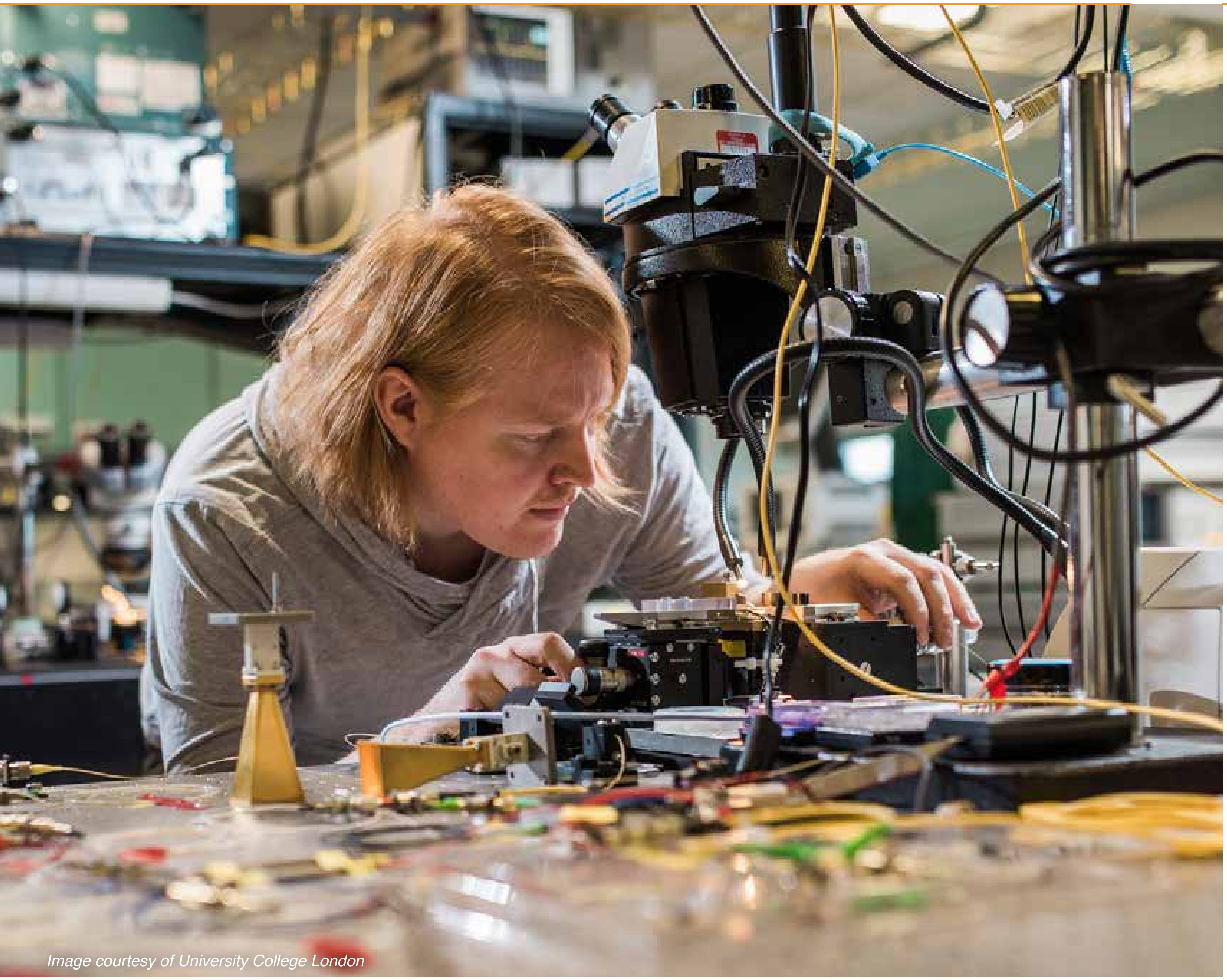


Image courtesy of University College London

Developments in detectors will support new and advanced sensing systems. Future devices will include **large imaging arrays, detecting simultaneously** at **multiple wavelengths,** extreme sensitivity devices, including **single photon detectors for short and mid-wavelength infrared regions** and **high-speed, high-sensitivity detectors in the visible spectrum.**

Data communications has become a cornerstone of society over the last 30 years. Optical fibre networks have shown an astonishing capacity to transmit data over global distances, delivering at a vast scale to meet society's ever-increasing demand for digital services. Continued demand for data, including the deployment of 5G, requires the development of **ultra-wide bandwidth optical amplifiers, modulators and optical fibres. Further use of coherent communications** and technologies exploiting **higher (THz) frequencies will also support expanding data capacity.**

The need to switch from the optical domain used to transmit data, to the electrical domain, used for data processing, routing and storage, is a major factor limiting overall network performance. **Large scale all-optical switches** and **fast random access optical memory** are essential milestones on the pathway to realising a fully **all-optical internet.** Together with non-volatile **read-only optical memory,** this will underpin the expansion of the digital economy by delivering improvements in speed, latency and bandwidth and will be a major step forward in reducing the energy consumption of data centres.

Photonic integrated circuits (PICs) incorporate hundreds of optical functions on a single chip, only a few millimetres square. These integrated devices are critical to the operation of today's cloud-based internet, creating a multi-billion dollar market for optical transceivers. The level of integration in these devices will continue to advance, first by enhancing and then going **beyond-CMOS integrated photonics and electronics,** improving energy efficiency, bandwidth and functional density.

In the same way that integrated electronics gave rise to a multitude of 20th century technologies, integrated photonics devices will open up many new opportunities beyond communications. Applications will include **optical-point of-care diagnostics,** augmented reality headsets, and integrated sensors for future cars and transport systems.

Integrating new materials and processes will enable **flexible, reconfigurable and programmable circuits** with increased adaptability and resilience for high volume applications. They will also help realise integrated devices for **quantum** and photonic **neuromorphic** computing.

Quantum computing offers significant promise for tackling a specific set of mathematical problems. Several competing technologies are in development and photonics has a role in them all, ranging from providing the core of the qubit engine to delivering key control mechanisms. Improving efficiency will be essential for photonics-based qubits. Even with current state-of-the-art single photon detectors achieving 80% detection, orders-of-magnitude redundancy is required to obtain sufficient logical bits. Advances in photonics, from lasers to sensors, will be a critical part of the roadmap **towards practical quantum computing at a scale of thousands of logical qubits.**

Developments in **quantum 2.0 devices for secure communications** and sensing will come hand-in-hand with advances in photonics. **Infrared, THz and microwave quantum communications** will unlock increased bandwidth and robust, long-range, free-space transmission. A full quantum-enabled network, reaching beyond today's point-to-point links, will require photonics-based **quantum repeaters and methods of entanglement distribution.** When combined with miniaturised integrated solutions, these innovations will open up **satellite and high-altitude quantum communications** for regions lacking wired network, for example, in shipping, war zones and areas hit by natural disasters.

"The applications of light have been as important as they are often visually impactful. It is exciting to get a glimpse of what is just over the horizon, and to think that we may have a part to play in making it a reality"

Dr Richard Carter, Heriot-Watt University

Methodology

Forward-looking ideas were captured from a cross-section of the photonics research community using an online workshop.

Participants were chosen by invitation from a cross-section of 20 UK centres of photonics research excellence. They included 22 internationally-renowned professors with a combined research income of over £650 million, well-placed to represent the views of the UK photonics community.

The experience of these senior academics was complemented by input from four early career research fellows (ECRs). The ECRs were selected by recommendation to represent the next generation of academics, those most likely to be leading photonics research ten years from now.

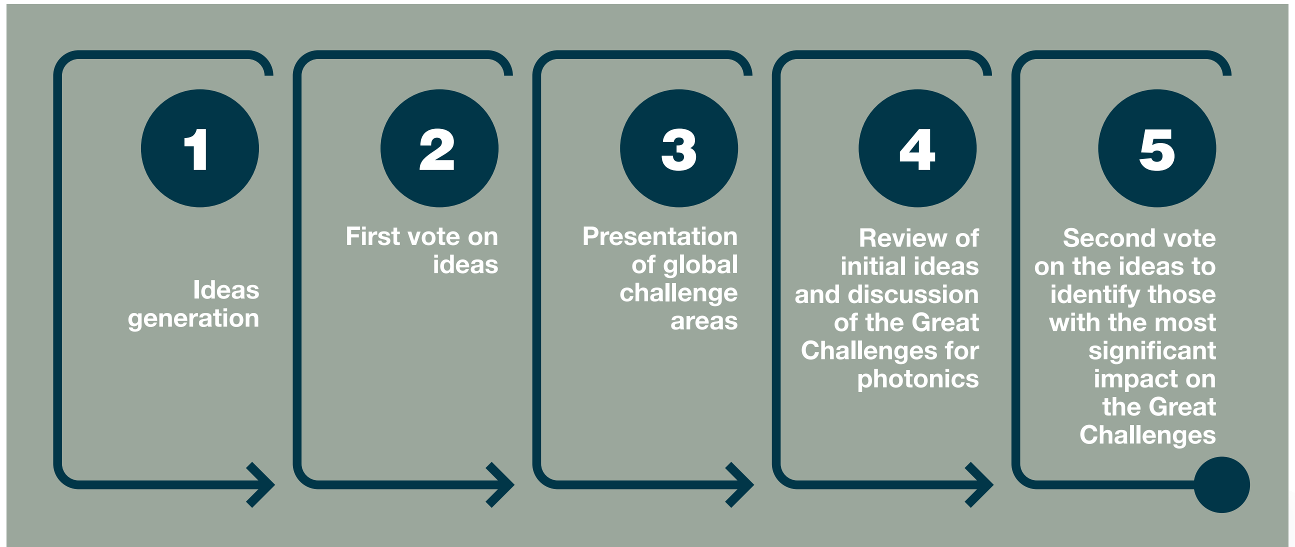
Observers from the Knowledge Transfer Network, Innovate UK, the Engineering and Physical Sciences Research Council (EPSRC) and the UK's Catapult network were also present. Two of the senior academics, unable to attend the live workshop, provided input after the event.

Workshop design

The horizon scanning workshop was designed by the PLG and ECRs, drawing on guidance in the Government Office for Science's Futures Toolkit and adapted for online delivery.

A five step process was used to elicit future concepts within the categories of: materials; optical and physical phenomena; future manufacturing processes and devices and systems.

Workshop process



Participants' credentials

Participants were brought together in a virtual meeting, chaired by Dr John Lincoln, CEO of the Photonics Leadership Group before being split into breakout groups, each with an ECR facilitator to stimulate interactions. Participants were brought back together for feedback, voting and discussions around the Great Challenges. The outputs from the group were captured using a digital whiteboard tool which also enabled vote casting.

The initial ideation session was preceded with a minimal briefing outlining:

- **Workshop objectives:** to develop an inclusive vision for UK photonics research to inspire and ensure continuing global leadership.
- **Basic boundary conditions:** looking 10 years into the future, at topics yet to become a significant research focus and/or where major directional changes may occur. Topics already at an advanced level of maturity were acknowledged to be outside the scope of the current discussion.
- **Context:** the horizon scanning workshop is the first of a three phase process to be followed with an examination of policy alignment and fit with the interests of industry.
- **Instructions:** using the virtual whiteboard tool.

The initial ideation generated 120 different ideas, 34 in materials, 19 optical and physical phenomena, 20 future manufacturing processes and 48 devices and systems. The facilitators organised the ideas into clusters where there were clear groupings and overlaps to aid subsequent voting (Step 2).

A summary of the major global challenges faced by photonics was presented to provide a basis for prioritising the initial ideas, based on an extension and update to the 2017 UK Industrial Strategy (Step 3). The group recommended adding an additional challenge area, photonics in food, resulting in a total of nine Great Challenges.

For Step 4, participants, in different breakout groups, were invited to take ideas from Step 1, along with any new concepts, and to position them along a scale indicating their potential to address the nine Great Challenges. Participants were then asked to vote on which ideas would have the highest impact on the challenges in ~15 years (Step 5). Due to technical issues, Step 5 was repeated after the live workshop.

Outputs and evaluation

The PLG led the compilation of this report, incorporating four technical sections written by the ECRs and comments and feedback from all the participants. Participants commented on the quality of discussion, diversity of ideas generated, and the efficiency of the exercise, indicating that the process was not adversely affected by being held as a 'virtual' event.

UK academics should transform the 70 ambitious topics on the photonics horizon into world leading research activity.

Research agencies should fund photonics research, investing in people, facilities and capability across the UK.

Researchers and funding agencies should strive for balance between materials, processes and systems innovation, leveraging their interdependency.

Policy makers are encouraged to support disruptive photonics research with impact on multiple societal challenges and markets.

Stakeholders should merge this research vision with industry demand and government policy.

Industrial Strategy Challenge Fund (ISCF) Directors should integrate these horizon scan findings with vertical market roadmaps.

The UK photonics community should champion this vision of the future of photonics to the world.

Recommendations

This scan of future horizons in photonics illustrates the strength, depth and diversity of imagination in the UK research community and reflects our long-standing position at the forefront of innovation.

The first recommendation of this report is a call to action for the UK researchers to convert the ideas articulated here into cutting-edge, world-leading research. Current research leaders should work with the next generation of innovators, embracing new approaches, striving for step changes in established areas of investigation and opening new research frontiers.

The second recommendation is for UKRI research councils and new initiatives under the proposed UK 'Advanced Research Projects Agency' to fully fund this flourishing of future photonics innovation. Their support is needed to develop people, facilities and capabilities in multiple institutions across the UK. Agencies should embrace the power of photonics to impact on many vertical markets simultaneously, with the global market for products enabled by photonics exceeding $2.6 trillion.

To best support the most advanced ideas captured in this report, it is vital to consider the natural harmonies and interdependencies which permeate through different photonics research areas. Developing new **systems and devices** involves innovating **processes** that leverage and adapt to new **optical phenomenon,** all of which depend on in-depth understanding and innovation in **materials.** The third recommendation, for agencies and researchers alike, is therefore to achieve balance between between different types of research, including novel phenomena and materials whose immediate device application is not obvious.

The fourth recommendation is for government and agencies to avoid excessive focus on a sub-set of topics, at the expense of new, potentially highly disruptive ideas. The very diversity of photonics impact means innovations in new and unlikely areas can have huge and lasting impact. Staying at forefront of innovation requires being in at the start, supporting new topics before they become mainstream.

The fifth recommendation is for this horizon scanning exercise to mark the start of a longer journey. The research ideas captured here should now be reviewed in the context of developing UK innovation policy, with a view to their future integration. Contributions from photonics and photonics-enabled industries should be sought, with their input used to refine and focus future research directions. Equally, this process should recognise that research has the potential to open up completely new paradigms – as Steve Jobs acknowledged: 'people don't know what they want until you show it to them.'

The sixth recommendation is to integrate this vision of the future for photonics with the roadmaps created for areas supported by the Industry Strategy Challenge Fund. ISCF directors are called upon to review the innovations identified here and to consider when, where and how they will drive and support solutions to their challenge areas. In prioritising research areas and their potential to impact on major global challenges, it is recommended that the views of the participants captured in this report should be considered but not be given undue weight. Prioritisation is naturally influenced by the participants' knowledge and recent events. All of the ideas presented are valid and will see advances in human knowledge. All have the potential to deliver huge impact and only time will tell which will lead to the Nobel Prizes of the future.

The final recommendation is for photonics users and innovators across the globe, to apply and disseminate the insights of this group of world-leading academics. Their collective vision provides a glimpse of our intertwined future.

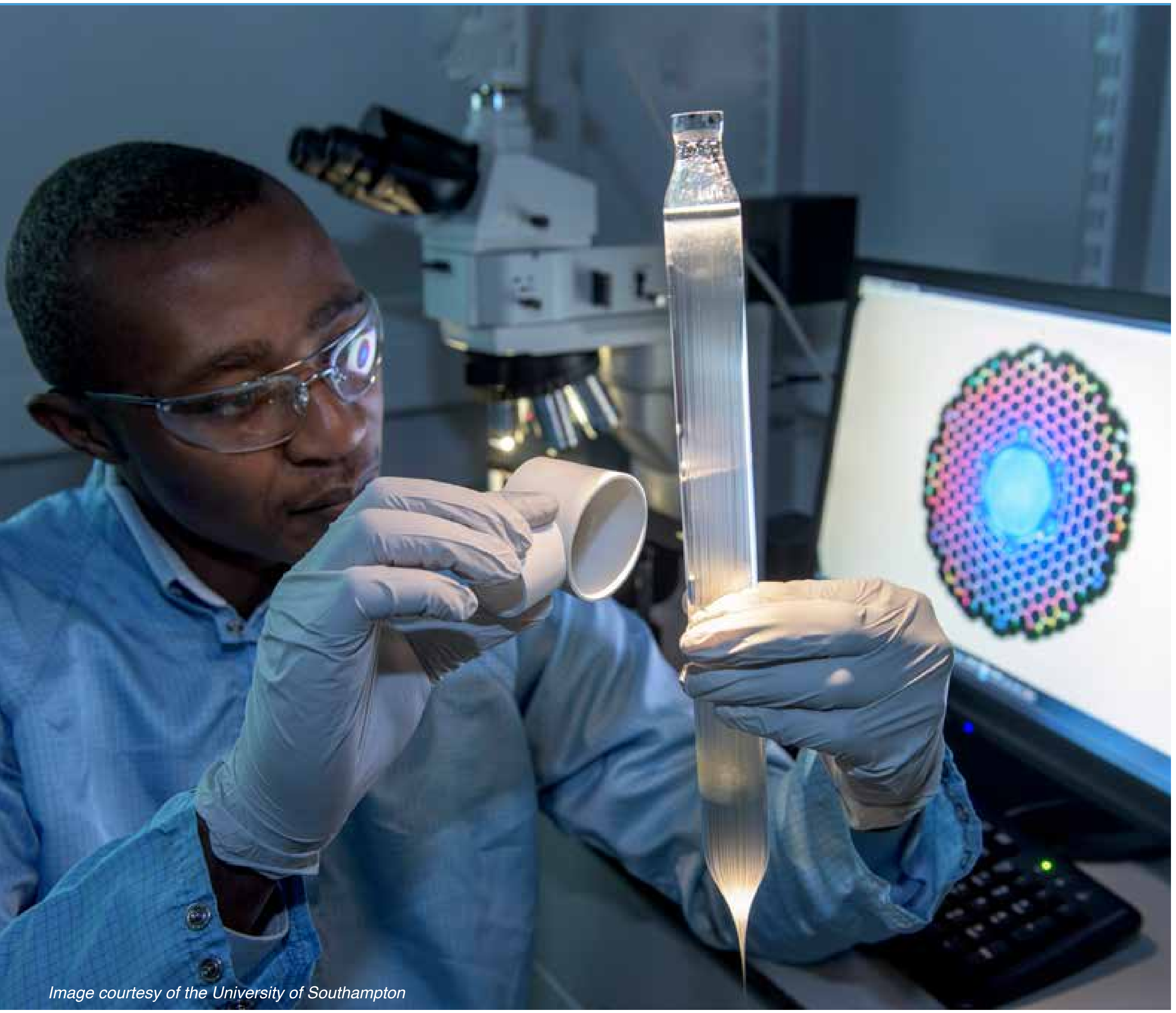


Image courtesy of the University of Southampton

Conclusions

Photonics has a bright and highly significant future. This scan of the ten year plus horizon reveals a huge variety of important new research ideas, for example, biodegradable photonics, neuromorphic photonics and AI-designed materials, where research is now in its infancy.

Other topics such as the all-optical internet, quantum communications and optical/quantum computing are already established but will see major new advances. It is also clear that integration, leveraging today's work in silicon photonics, will become pervasive, covering many more materials and almost all applications.

Building on the heritage of Maxwell and Newton, the UK has been at the international forefront of photonics research and innovation for over 300 years. The modern internet is founded on a global network of optical fibres invented in the UK by Nobel Prize winner Charles Kao. Nearly everyone now carries a smart device with them, everywhere they go. The screens, cameras, sensors and connectivity in smart phones all depend on photonics with lasers widely used in their manufacture. The next era of digital economy, autonomy and smart manufacturing will depend even more on optical technology to interact with the world.

Photonics is already the 14th largest UK manufacturing sector, similar in size to pharmaceutical manufacturing and fintech, both in terms of output and employment. Sufficient demand from global markets is available to grow the UK photonics industry significantly, feeding it with cutting-edge innovation. Increasing the use of photonics across the UK economy offers the opportunity to leverage even greater impact, by making the UK a key adopter, as well as the lead producer, of photonics knowledge.

Only by following the recommendations of this report to support the rich spectrum of photonics research at the edge of the horizon will the UK be able to lead the world in developing solutions to major societal challenges. Integrating this vision of future photonics research with the demands of policy, vertical markets and global challenges will enable the UK to lead the world in capturing the value that light offers to us all.

Acknowledgements

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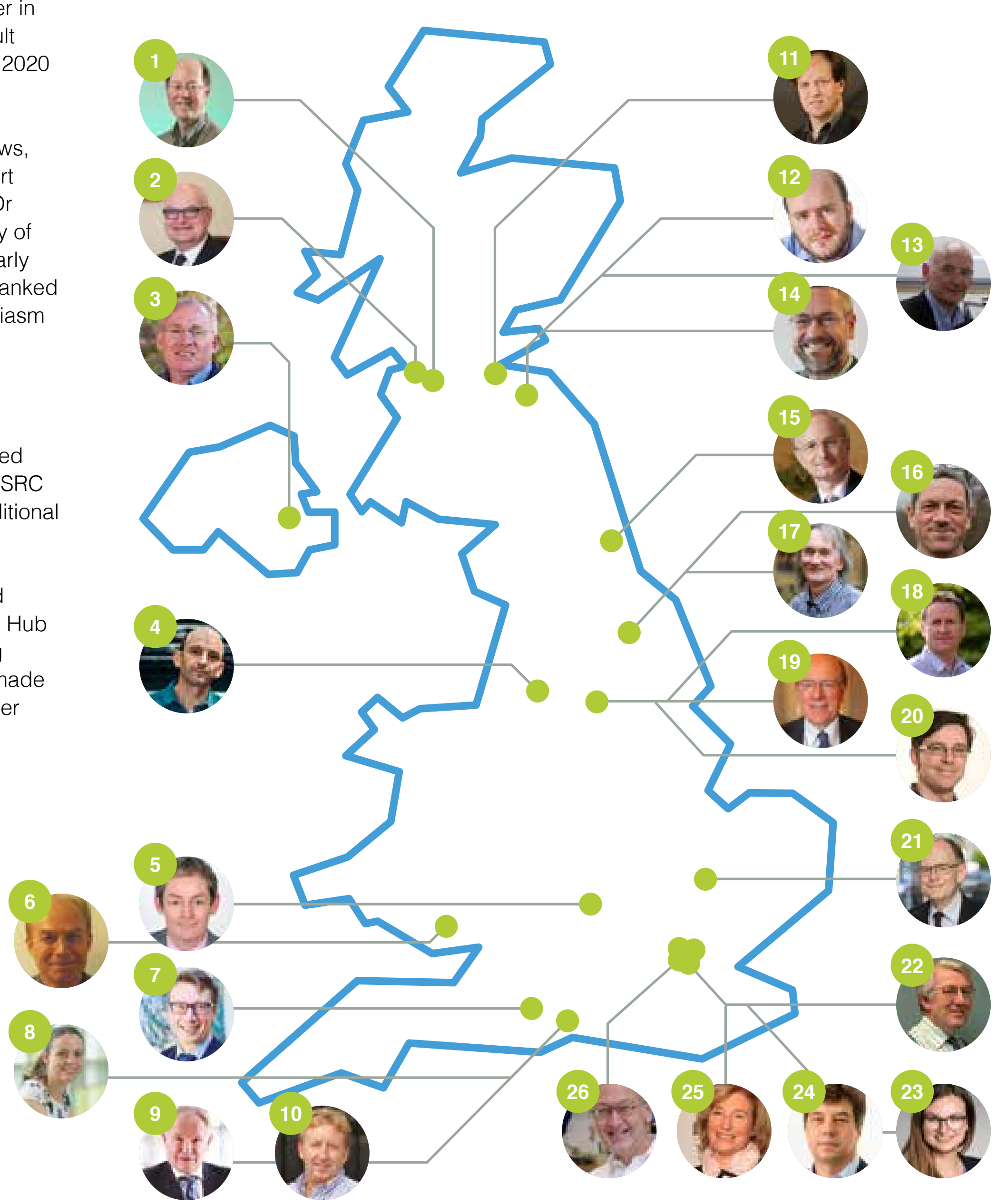

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References:

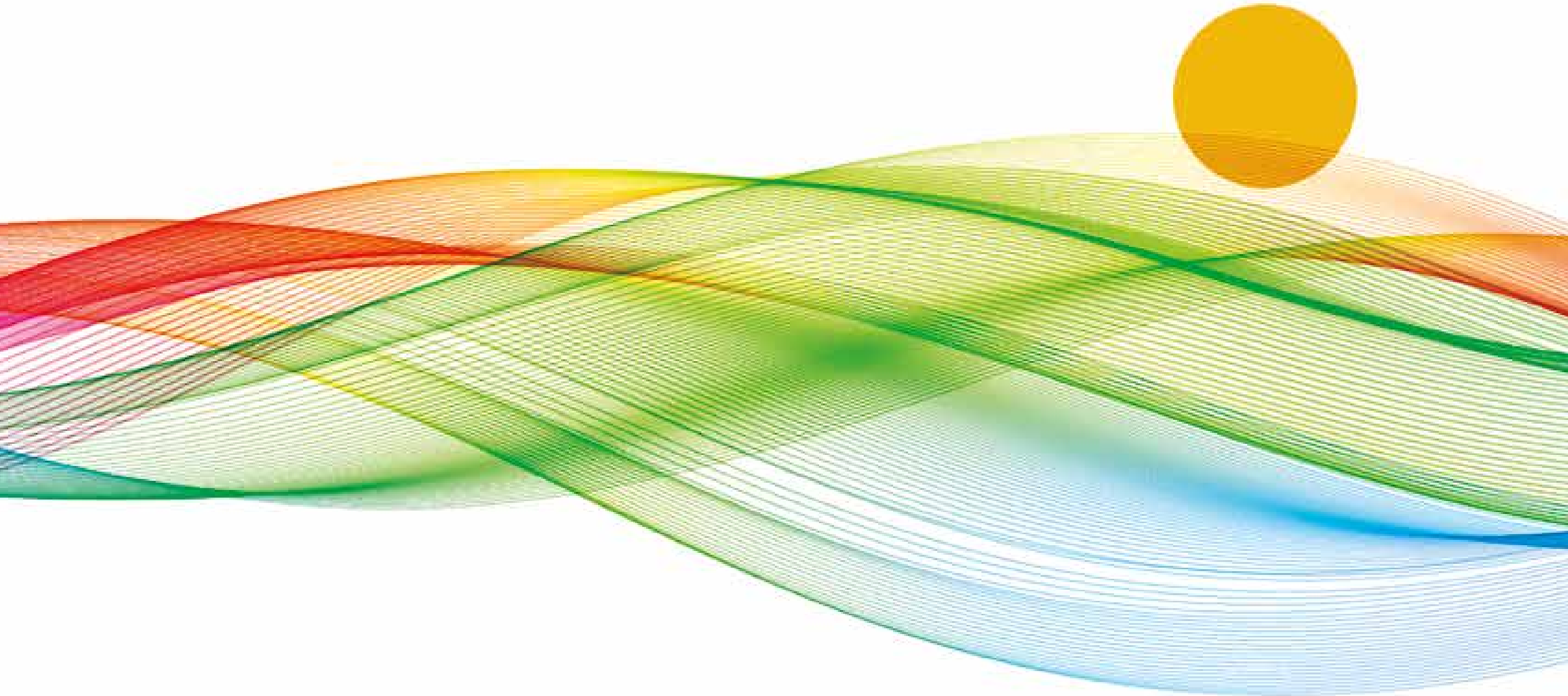
UK Photonics: The Hidden Economic Engine (2018), www.photonicsuk.org

UK Photonics Industry 2019 Update, www.photonicsuk.org

Futures Toolkit: tools for strategic futures for policy-makers and analysts (2017) ww.gov.uk/government/publications/futures-toolkit-for-policy-makers-and-analysts

Industry Strategy: building a Britain fit for the Future (2017) UK industry strategy, www.gov.uk/government/publications/industrial-strategy-building-a-britain-fit-for-the-future

Optics and Photonics Industry Report 2020, SPIE, https://spie.org/news/2020-optics-and-photonics-industry-report



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