

dti

FORESIGHT

Exploiting the
electromagnetic spectrum:
Findings and analysis

OFFICE OF SCIENCE AND TECHNOLOGY



The DTI drives our ambition of 'prosperity for all' by working to create the best environment for business success in the UK. We help people and companies become more productive by promoting enterprise, innovation and creativity.

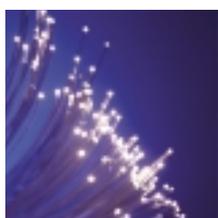
We champion UK business at home and abroad. We invest heavily in world-class science and technology. We protect the rights of working people and consumers. And we stand up for fair and open markets in the UK, Europe and the world.

Contents



Introduction

1



**Switching to light:
all-optical data handling**

5



**Manufacturing with light:
photonics at the molecular level**

11



**Inside the wavelength:
electromagnetics in the near field**

19



**Picturing people:
non-intrusive imaging**

29

Findings and analysis

Introduction

The Foresight project on 'Exploiting the electromagnetic spectrum' (EEMS) set out to provide a vision for the future exploitation of the electromagnetic spectrum to ensure increased UK innovation in selected areas. The project aims were to identify key areas of long-term opportunity across the spectrum, assess these against UK capabilities and agree a plan of action to help the UK exploit these areas. The project focused on four topic areas, selected through a rigorous scoping process involving the academic, business, and user communities, along with representatives from other government departments and funding bodies.

Project process

The scoping phase of the project, which culminated in the selection of the four topics, was based around two workshops. The first workshop brought together a small group of scientists from business and academia, and focused on the science push. It identified around 20 areas of exciting research with application potential. These ranged across the whole spectrum and included technologies for: more efficient use of the radio frequency spectrum in mobile communications; increased data communications capacity; better and less intrusive sensing and imaging; and manipulating molecules and materials on very small scales.

The second workshop brought together a much larger group of business and user representatives and focused on the market pulls for the technologies identified by the first workshop. This resulted in a shortlist of nine topics where there was felt to be both a clear market demand, and hence exploitation opportunity, and a strong UK research base from which to start. Four of these were selected against the following criteria:

- **far out and innovative:** major economic activity 10–20 years hence; currently

unanswered science problems; potential for step-change in technology

- **economic significance:** potential global market size; UK market size
- **UK ability to exploit:** UK share of market; UK export value; skills base; UK science base
- **balanced topic portfolio:** science-versus application-driven; cross-disciplinary; spread across spectrum; stakeholder support.

The four selected topics were:

- **Switching to light: all-optical data handling**
- **Manufacturing with light: photonics at the molecular level**
- **Inside the wavelength: electromagnetics in the near field**
- **Picturing people: non-intrusive imaging**

For each of these topic areas, expert action groups were convened to identify the technical challenges and business opportunities, and develop plans for action. Members were drawn from business, academia, user communities, government and other agencies. As part of this process, state of the science reviews for each topic were commissioned from a member of the action group, and endorsed by the rest of the

group. The reviews look at new technological advances, assess their likely impacts over the next 10–20 years and consider the UK's relative strengths in these areas. They are available on the CD-ROM that accompanies the Foresight EEMS launch pack and on the project website at: <http://www.foresight.gov.uk/emspec.html>. Short and accessible overviews of the state of the science reviews are also available, in hard copy and on the website.

The reviews informed the first action group workshops, which focused on potential applications and their underpinning technologies. The groups developed detailed 'technology timelines', mapping out the intermediate steps needed to deliver a few exemplar applications. Streamlined versions of the key timelines are included in this report. Non-EEMS technologies were sometimes highlighted in this process – for example, software for data analysis (particularly images), and advanced materials development. In some cases, non-technological issues were also highlighted as key barriers to exploiting or creating markets.

Two pieces of economic work fed into a second set of action group workshops, which focused on selecting the most promising markets and applications for the UK to exploit, and identifying actions to help the UK realise these opportunities.

We commissioned Professor Andrew Stark, Professor Dean Paxon, Professor David Newton and Dr Martin Widdicks from Manchester Business School to develop an easy-to-use evaluation tool to help assess potential investments in research and development (R&D). This tool draws on existing real options analysis, which has come to the fore in recent years as a means of capturing the value of the flexibility embedded in long-term, multi-stage, R&D projects in the presence of inevitable uncertainty. Based on well-developed techniques used in financial markets to value the right, but not the obligation, to buy an asset in the future, real options analysis is gaining in acceptance as an important tool in assessing R&D proposals. The tool provides a framework to ensure that key milestones are set for decisions on further investments and helps make clearer what the risks and uncertainties are.

It helps identify the scale of the upside – the potential returns in the unlikely (but possible) event that success exceeds expectations. In a portfolio of investments, it is these few big wins that provide the overall return. The tool allows users to experiment in an iterative way with different parameter values and proposal structures, and provides analysis of the sensitivity of the value to input parameter changes. Spin-off benefits can be factored in, if they can be quantified.

We also commissioned a market research company (FreshMinds) to assess the possible market sizes for the applications identified by the action groups as offering the greatest potential. Estimating market value was particularly challenging in some instances as there is no existing market, and the project's 10–20-year timescale is beyond that of much market data. Care should thus be exercised in any use of the market estimates in this report.

At the second set of workshops, the action groups reviewed the market data and drew on it to develop their own estimates for the market size, the fraction capturable by the UK and the investment costs needed to get to market. In making these estimates (best guess plus 20% upper and lower bounds), the groups considered competition from other countries and other technologies in meeting the demand.

These figures helped inform the selection of a few key opportunities from the many possibilities originally identified.

This document presents the main findings of the action groups for the four selected topics.

We were greatly helped throughout the project by Professor Will Stewart, former Chief Scientist at Marconi and the project's expert advisor, and by Dr Rob Phaal of the Institute for Manufacturing, Cambridge University, in developing the structure of the workshops.

The project's sponsoring Minister, Stephen Timms MP, DTI Minister for Energy, e-Commerce and Postal Services, convened a stakeholder group to oversee the work of the project. The group is actively involved in carrying forward action as a result of the project.

Stakeholder group members

Dr David Clark, Director of Research and Innovation, Engineering and Physical Science Research Council (EPSRC), replaced by

Professor Randal Richards, Director of Research and Innovation, EPSRC

Professor Trevor Clarkson, formerly Head of Engineering and Research, Radiocommunications Agency, now head of External Research Management, Ofcom

Sir Anthony Cleaver, Chairman, Medical Research Council (MRC)

Anthony Dunnett, formerly Chief Executive, South-East England Development Agency (SEEDA), replaced by Professor Ed Metcalfe, Head, Science Technology Entrepreneurship and Management, Learning and Skills, SEEDA

Martin Earwicker, Chief Executive, Defence, Science and Technology Laboratory (DSTL)

Dr Peter Greenaway, Assistant Director of Research and Development, Department of Health

Dr Hermann Hauser, Director, Amadeus Capital Partners Ltd

Professor Richard Holdaway, Director of Space Science and Technology, Council for the Central Laboratory of the Research Council (CCLRC) Rutherford Appleton Laboratory

David Hughes, DTI Director General Innovation Group, project director

Peter Ingram, formerly Chief Technical Officer BT Retail, now Chief Technical Officer Ofcom, replaced by

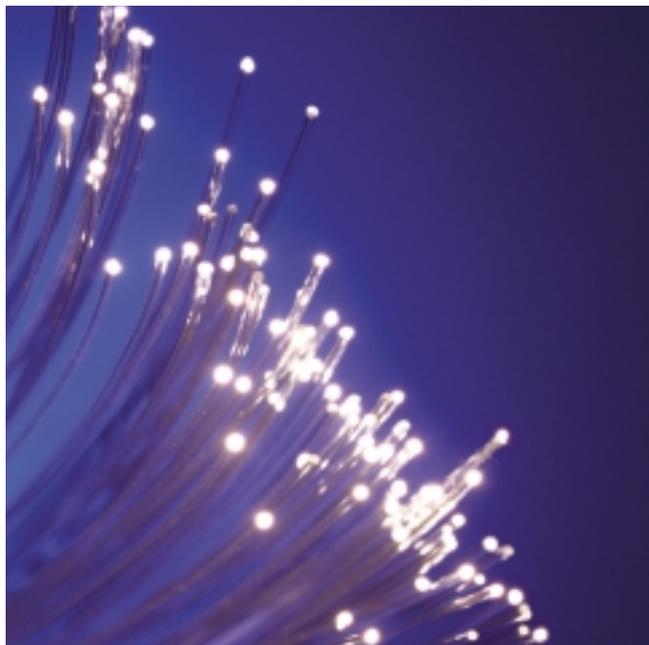
Professor William Webb, Head of Research and Development, Ofcom

Dr Andrew Rickman, Chief Executive, Bookham Technology plc

Professor Michael Walker, Group Research and Development Director, Vodafone Group

Professor Colin Webb, Founder, Oxford Lasers Ltd

Switching to light: all-optical data handling



Summary

Over the last 20 years, optical fibre has become the dominant long-distance transmission medium for data communications, with copper wire (or radio) used mainly for the 'last mile' link to the user. Although data is now transmitted optically, routing and switching continues to be carried out electronically. For current and near-future data-traffic demands, this is both cost-effective and adequate. But if widespread demand reaches terabit levels (one terabit per second = 10^{12} bits per second), existing and easily foreseeable electronic technologies will have difficulty keeping up. Optical techniques will then need to form an increasingly large part of switching and routing systems in order to satisfy expected future traffic levels. **The UK could capture a market of \$0.5 billion in 10 years' time in fast optical switches, if it invested now in the UK's excellent science expertise in this area.** This is a high-risk venture, because of the uncertainty over whether fast optical switches will be needed by then, the likely global competition and the risk that the UK will not

have a home market, which is perhaps essential to compete successfully in the world market.

The key issue for the development of a home market is the provision and use of high-rate (100 Megabit/sec) broadband to the home/user. **The decision to roll out high-rate broadband for all rests on wider economic and social considerations but, if taken now, would offer the chance that the UK might also capture the commercial opportunities.**

Introduction

The cost and energy burden of converting signals from optical to electronic and back again when processing and routing becomes ever greater as data networks become more complex and data rates increase. Conversion could be avoided if these functions were carried out optically. The low cost and logic-friendly nature of silicon means that it is likely to remain unbeatable for certain functions but, above some data capacity threshold, further increases in capacity will only be delivered through increased use of optical components in new hybrid optical/electronic systems.

These hybrid systems will provide complex networks with the flexibility and performance to evolve to meet ongoing future requirements of local broadband systems and distributed computer processing. Promising hybrid systems under investigation keep the data signal in optical form but attach a routing label that is processed electronically. New network architectures that reflect features of optical processing (such as burst processing of signal packets) will also be needed.

There are major science and engineering challenges to the commercial production of optical components. For example, a critical part of optical processing is an optical photonic memory with a performance to match or exceed

that of the ubiquitous electronic RAM (random access memory). At present there is no method of storing and reading out data optically although a variety of methods are under investigation.

Other techniques that could enable fast optical switching, including nonlinear optics and fast tuneable lasers, are also advancing rapidly. Photonic bandgap structures which can compress light into very small spaces, making devices much more efficient (and potentially lower cost), appear particularly promising.

Key drivers

For there to be a market for fast optical switches, the action group agreed that demand for data transmission rates would need to reach terabit level in the network.

Such demand would be generated by a 'knowledge economy' where value is placed on fast access to increasing amounts of globally accessible information. If the future is moving towards a world of remote working – and playing – in the widest sense of connecting in a data-rich way with experts or databases at a distance, the capability of existing technologies to deliver the necessary information to the right place in an acceptable time will be put under increasing strain.

New data is currently being generated at a rate of 2 exabytes (2 million terabytes) per year (250 megabytes for every person on earth). Companies rely ever more heavily on computerised records, and legal obligations to keep data are growing. Increasing personal use of information technology is likely to lead to a growth in demand for consumer data backup facilities. Stored information is useless without rapid access for all who need it.

In addition to the corporate knowledge economy, there are other data-transmission-intensive markets, particularly ones such as video and telepresence involving images, which might drive network demand to terabit levels. These include: multimedia consumer gaming and video-on-demand; remote management of disasters by experts; comprehensive security systems; and fully integrated electronic patient records.

It is difficult to estimate how fast demand is growing, and thus when it might reach terabit level, but most estimates are in line with the recent comments of Eric Mentzer, Intel's Vice-President and Chief Technology Officer:

'[Broadband and new multimedia applications] are going to continue to drive bandwidth on the optical backbone... The net result of all this is incredible growth in the Internet. What is our network going to need to scale to? It will be about a thousand times. If it keeps up with this, which we think it will, we'll need a network that can carry a thousand times as much traffic ten years from now.'¹

Current capacity to broadband-equipped homes in the UK is ~1 Mb/sec (one megabit is 10^6 bits). A thousandfold increase takes this to 1 Gb/sec (one gigabit = 10^9 bits), which corresponds to data rates of hundreds of terabits in the network backbone. A more cautious estimate of 100 Mb/sec to the home in ten years would still imply the need for fast optical switching.

Although global markets for fast optical switching technology could exist without there being a UK home market, a home market is probably essential if the UK is to build an industry in this area. Growth in demand in the UK is presently hampered by a lack of broadband capacity, and without access, demand cannot grow. This barrier is principally economic: the cost of providing fibre to the home to around 95% of the population is estimated at £10–20 billion. The current open-access-to-infrastructure regulatory framework in the UK reduces the incentive for individual companies to invest in infrastructure. Whilst consumers may be prepared to pay for infrastructure if there are 'must have' applications they desire, this is unlikely to create network-wide demand fast, and is also something of a chicken and egg situation. A workable business model to support investment is needed. Japan is currently rolling out a 100 Mb/sec subscription service, but costs per capita would be much higher in the UK (due to lower population densities and underground

¹ Eric Mentzer, Optical Fiber Conference 2003

installation of fibres – the Japanese are installing them above ground).

The group's assessment was that a public policy initiative would probably be required to bring high-rate broadband to the home. This could take the form of regulatory changes to allow businesses to keep control of their own investment in infrastructure, or to make installation compulsory in new buildings. **Whilst wider social and economic considerations are likely to be the primary motivation for a high-rate broadband initiative, a clear and early decision would allow the possibility that the UK might also benefit commercially as well.**

Markets and applications

Delivering terabit-level data rates will require fast optical switching and routing systems. Rather than replacing existing electronics systems with all-optical ones, the new systems are likely to be hybrid, with optics fulfilling the requirements that electronics will not be able to meet. The main application areas identified for the use of optical technologies within the network were:

- storage area networks
- GRID equipment
- computer interconnects.

These would provide the network infrastructure for high-capacity connections to storage, and fast retrieval and processing of data in distributed databases. Off-site data storing needs to be easy

for the user, fast and secure, and allow for large spikes in demand (such as end-of-the-day backing up). To be most efficient, the network needs to be dynamic, user-defined/controlled and fully integrated. Rather than the route a signal takes being assigned by the network operator, the route would be decided by the user. There are many issues of data privacy, legal and industry standards, copyright and protocols to be defined. Industry standards, which could have important knock-on effects, are likely to be determined by the main players. To have a say in establishing standards the UK needs to be part of this new industry. It is likely that new business models for selling services will evolve to reflect the features that the customer regards as most valuable.

The action group's 'best guess' estimate for the value of the global market for fast optical switches in 8–10 years' time was \$16 billion. They thought that the UK could capture a share worth \$0.5 billion (see Table 1). An investment of around \$15 million is required for the initial 5-year research phase, which would result in a packaged prototype switch with a demonstrated route to scaling the port count (with passive assembly). The milestones for the short second and third phases would be, respectively: developing a repeatable process for fab/packaging large port count switches with initial reliability testing; and fully qualifying this process, adding electrical interfaces, automated assembly and customer sampling. The total time to market was estimated at 8.5 years.

Table 1. Market estimates for fast optical switches

	Investment costs – three R&D phases plus one-off pre-production costs							
	Phase 1 Initial investment (duration)	Phase 2 (duration)	Phase 3 (duration)	Pre- production (duration)	Total investment cost (total duration)	Value of UK share of market	World market	UK share
Best guess of UK market size	\$15 million (5 years)	\$20 million (1 year)	\$30 million (1 year)	\$150 million (1.5 years)	\$215 million (8.5 years)	\$0.5 billion	\$16 billion	3%
Optimistic market size (20% likelihood)						\$32 billion	\$160 billion	20%

The group's optimistic estimate (20% chance) of the value to the UK was \$32 billion. The very large spread in value reflects the highly uncertain nature of this investment, which would involve setting up new robotised production methods and competing against the US and others who are already investing heavily in the basic technologies. The UK is, however, well placed in terms of photonic and system expertise, and many of the underlying technologies will have spin-off applications to provide revenue stream along the way. **The high degree of uncertainty, together with the small initial investment costs make this an attractive option since the cost of 'staying in the game' is low compared to the potential returns, and the major investment costs are those of pre-production, which may be deferred until later.**

On a longer timescale (beyond 15 years), the group considered that niche applications taking advantage of specific optical properties might emerge outside the communications sector. For example, optical pattern recognition techniques for reading data labels could find wider use in pattern matching. In the even longer term, the group noted that storage, rather than access, may become the bottleneck, although solutions to this are unlikely to be optical.

Technologies

At the heart of the anticipated optical hybrid network would be fast (below 10 nanoseconds) optical switches, initially in 100 x 100 port count arrays. In these switches, light would act directly and efficiently on other optical signals, routing them without the need for an electronic intermediary. To do so requires various combinations of:

- wavelength-agile components, using cheap tuneable lasers so that signals can be switched by changing their wavelength
- hybrid integrated, scaleable component arrays for space switching
- optical buffer memory to store signals for bit-level switching, likely to involve using photonic bandgap structures in the future
- multi-wavelength optical regeneration components to restore degraded signal strengths
- scaleable Optical-Electronic-Optical (OEO) edge routers to handle the interface between optical and electronic processing.

These components will need to be power-efficient, scaleable and low cost. Their development will depend on more generic integrated photonic platform technologies, dense integrated optics and materials with very high nonlinearities. Cheap compact tuneable short pulse lasers are also essential.

Other important issues include developing future-proofed (dynamically reconfigurable) network architectures to play to the strengths of the new switching technologies.

In addition to the unanswered basic research questions, there are significant new production-advancement requirements, including:

- high-yield reliability monitored fab/automated production of switch arrays
- uncooled optoelectronic components, with thermal management of the arrays
- development of a cost-effective hybrid integration platform for photonics and electronics
- protocols and standards (quality control).

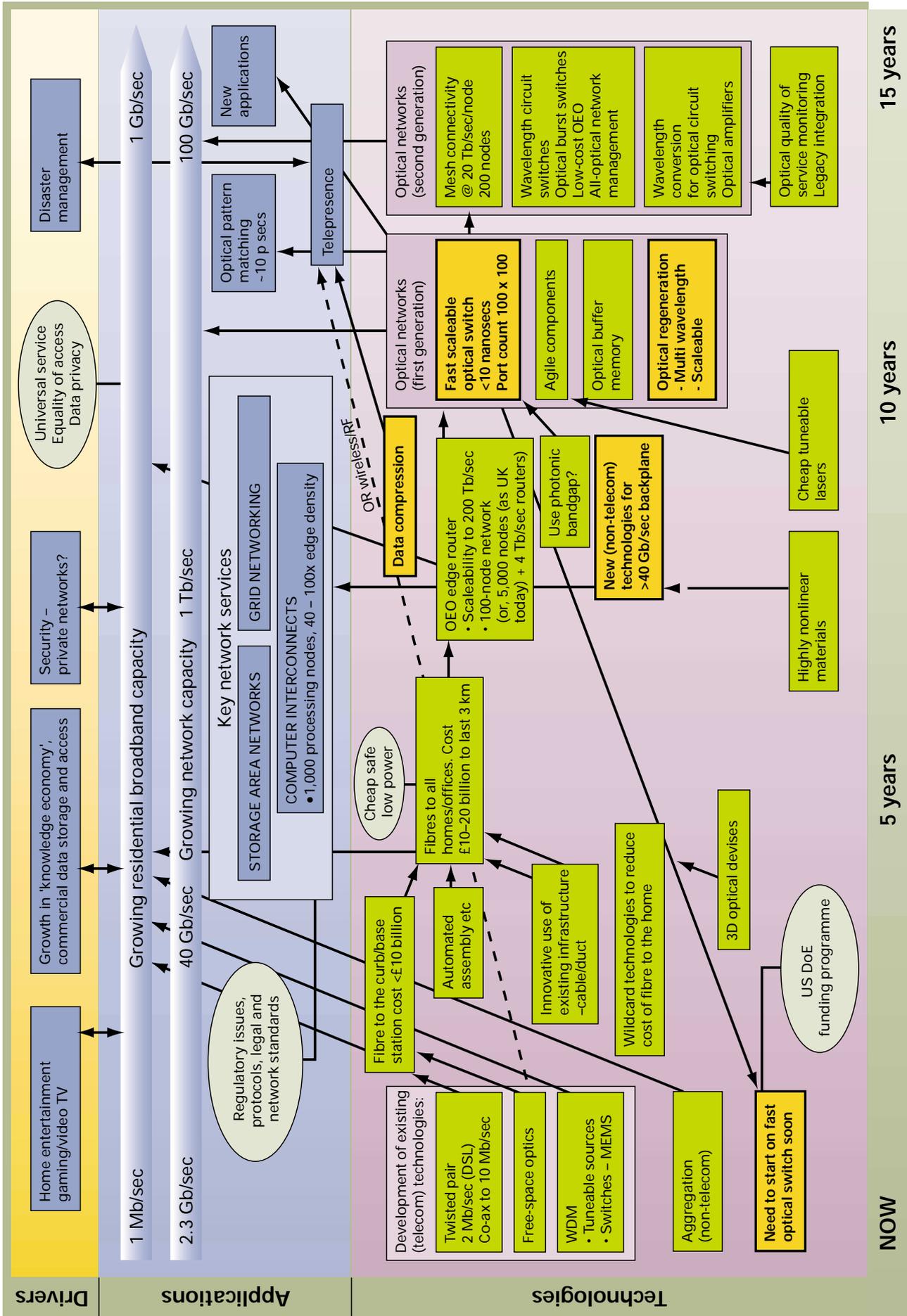


Figure 1. All-optical data handling: technology timeline for fast optical switches (key steps shown in orange)

The way forward

If demand for network data transfer rates were to reach terabit levels, it would exceed the capabilities of existing switching and routing technology. The UK is well placed to develop fast optical switching technologies to meet this need. The UK might capture a share of the global market of between \$0.5 billion and \$32 billion. There are a number of issues to be considered:

- the uncertainty as to whether or when fast optical switches will be needed
- the risk that the UK will not have a home market, which is perhaps essential to compete successfully in the world market
- the likely global competition.

The key steps to help the UK maintain its lead in the science in this area and keep open the option for further investment at a later stage to capture a share of the market, should the demand arise, are:

- **a co-ordinated and visionary strategy by the photonics community**
- **an initial investment of around \$20 million in R&D, to support existing UK centres of research excellence in integrated photonics technology. Research should be industry-led to leverage this investment effectively**
- **a commitment to high-bandwidth broadband rollout.**

Since many of the underpinning technologies (for example, cheap tuneable lasers and cost-effective hybrid integration platforms) will have extensive use in other applications and markets, activity should probably form part of a national photonics roadmap providing a strategy for photonics both in and outside of the communications sector (that is, combining with the 'Manufacturing with light: photonics at the molecular level' topic recommendations).

This opportunity, among others, will be considered by the DTI Electronics team's newly formed Photonics Strategy Group, which will identify opportunities and challenges for the UK over the next 5-10 years and develop an action plan to exploit

the sector. The team is also working to bring together key players to start a national Photonics network along the lines of the successful Fuel Cells initiative.

Photonics has also been identified as a potential priority area for a Call in 2004/05 under the new DTI Technology Strategy.

Acknowledgements

We would like to thank all members of the action group who gave so generously of their time and expertise.

Ron Ballingall, DSTL

Dr Peter Batchelor, DTI

Professor Polina Bayvel, University College London

Dr Andy Carter, Bookham Technology plc

Dr Russell Davey, BT

Dr Michael Dueser, University College London

Steve Ferguson, Marconi

Dr Patrick Gill, National Physical Laboratory (NPL)

Professor Michael O'Mahoney, University of Essex

Vince Osgood, EPSRC

Professor David Payne, Southampton University

Dr Alistair Poustie, Centre for Integrated Photonics

Ian Williams, DTI

State of the science review authors: Professor Polina Bayvel, Dr Michael Dueser and Professor John Midwinter, University College London.

Manufacturing with light: photonics at the molecular level



Summary

Lasers have long been used for precision machining but as control becomes ever finer and faster, light now offers the ability to manipulate matter on a molecular scale.

Laser micromachining in three dimensions offers many manufacturing opportunities, such as the fabrication of microstructured materials for next-generation solar cells, smart fibres, photonic crystals and photonic lab-on-a-chip devices.

The UK could capture a \$5 billion market in integrated lab-on-a-chip systems, as a platform technology for a number of multi-diagnostic applications, including diabetes treatment, health monitoring, drug targeting and cancer detection. In the longer term, this could lead to therapeutic applications, though these require an order of magnitude more investment in regulatory trials. Extrapolating the historical market growth rate and current size, this lab-on-a-chip market could be \$100 billion by 2012. Capturing a niche of

even 5% of this is a significant opportunity that the UK is in a strong research position to address. **These applications tend to have high capital costs of setting up production, but the potentially huge markets mean that the relatively low initial research investment costs are an attractive, if risky, proposition.**

Introduction

More and more new developments in microelectronics, integration and micro- and nano-technologies require three-dimensional structures, often made from materials that are difficult to work with. Laser machining is adaptable to a wide range of materials and is surprisingly gentle (able to cut soft and biological materials without damage) so will play an important part in the production of these microstructures.

Large-scale precision machining did not form part of the scope of this topic, and the action group identified two broad areas for the focus of their work.

Micro and nano fabrication techniques now being demonstrated in research laboratories could, if commercialised, produce the kinds of multiple-material microstructures needed for a wide range of applications including next-generation solar cells, smart fabric, intelligent fibres (sensors) and photonic crystals. A particularly promising application is the fabrication of an advanced lab-on-a-chip (LoC).

Integrated photonic LoC will, in addition to being fabricated using photonic and laser technologies, also rely on them for its functional capabilities. Current LoC devices are mainly passive microarrays of up to tens of thousands of test sites at which are located specific molecules or chemicals that test for a particular function. DNA chips, in which the test molecules identify particular genetic sequences,

are the most common, but protein arrays are also an important market.

An integrated photonic LoC would actively sort molecules or particles using arrays of lasers ('optical tweezers') to push different molecules in different directions as they flow through the 'optical lattice' created by the laser beams. Preliminary experiments have shown possibilities here and exciting new developments in lasers and photonics offer the prospect of integrating many other specific functions on a single chip to offer multi-diagnostic capability in the future.

Key drivers

The market drivers for specific applications of laser/photonic micromachining are diverse. With increasing pressure on global energy resources, improved energy efficiency (particularly, though not exclusively, for portable devices) is set to become an ever more important consideration across the board. Cost reduction and miniaturisation/portability are common drivers in manufacturing, which are bolstered by trends towards increasing personalisation of service delivery. They can also drive the opening up of new markets and 'throw-away' applications. Demand for environmental monitoring is rising: comprehensive surveillance of pollution or natural resources requires small cheap low-maintenance sensors.

The overarching long-term driver for LoC applications is healthcare and the rising expectations of ageing but affluent societies prepared to pay for the best available care. Fast, efficient multi-diagnostic tests are an essential part of evidence-based diagnostics.

They improve prevention, detection and treatment of disease, and the matching of treatments to the specific needs of individual patients.

In recent years, it has become increasingly clear that genetics affects not only predisposition to disease but also the efficacy of current generation drugs. As Dr Allen Roses of GlaxoSmithKline recently acknowledged, as many as 90% of prescription drugs work in only

30–50% of the population. Despite the significant ethical issues surrounding genetic testing, the benefits in terms of preventative and prescriptive treatments are likely to prevail and lead in the long term to the individual tailoring of drugs. This science of pharmacogenomics offers the prospect of far better-targeted and efficient prescribing, screening patients both for the most appropriate drug and for those likely to cause them adverse reaction. Greater prescribing efficiency also promises large potential savings on drug spending, although whether this would lead to any reduction in overall spend is unclear (the savings may simply be used to make more expensive drugs available to more people). In due course this could lead to highly personalised 'chip therapy', but because of the considerable regulatory hurdles faced by new therapeutics, the action group felt that over the next 10–20 years the driver for LoC in healthcare would be diagnostic rather than therapeutic.

In the shorter term, and covering the period where any new healthcare diagnostic would be required to undergo trials, photonic LoC technology offers the prospect of meeting demand for more efficient development of new pharmaceutical drugs (where the discovery cycle currently takes 10–15 years). It is also likely to provide better research tools across a range of biosciences, including exciting areas of research such as genomics and proteomics.

The growing demands for many types of environmental monitoring – pollution, food toxins, chemical hazards – may provide a market for chemical use of LoC technology. There are, however, many competing technologies in these sectors, so chemical uses are unlikely to be the main drivers for development (at present, virtually all uses of LoC are biological, so much so that the term 'biochip' is used almost synonymously).

Markets and applications

Micro and nano fabrication

Micro and nano scale fabrication methods will have a wide range of applications. The action

group considered in detail the market for **three-dimensional microstructured materials** for next-generation solar cells, low-intelligence microfibres for distributed sensing (of the environment, fire, biohazards), fabrics and paints for camouflage. The photovoltaic solar cell market is currently dominated by Japan, who account for 70% of the manufacturing capacity in a market with significant overcapacity at present, although this is likely to change as use of fossil fuels becomes more expensive.

The group estimated that the UK might capture 20% (\$2 billion) of a market worth \$10 billion in 12 years' time, for a total investment of \$580 million. They estimated that there was a 20% chance of the market being \$30 billion and the UK capturing 25% of it. The goals of the three phases of research were defined as: (1) a scaleable manufacturing technology for making smart fabric and solar cells from a single material; (2) the same output but made from a number of materials bonded together (junctions between different materials is a particular issue); (3) development of packaging, integration and prototyping. The phased stages of the investment costs make this a reasonably appealing proposal.

The group also considered the smaller market for the fabrication of **application-specific polymers** produced in a minifab foundry, and the **litho tooling** market – making the manufacturing tools rather than the end, user devices. At present the principal known

application for these tools is display screen manufacture. The key research phases here involve developing reconfigurable masks using spatial light modulators, and developing new resist materials in three dimensions, to achieve etching of giga-pixel resolution, but the high investment costs make this less suitable for UK exploitation.

Integrated photonic LoC

The short-term market for photonic LoC will be in research and development laboratories, enabling high-throughput precision-controlled synthesis of chemicals and biochemicals for biological purposes, and sorting and selection of particles and molecules. This market is a high-end, high-cost, low-volume one, in contrast to the slightly longer-term healthcare diagnostic market, where the cost of a test will need to be comparable with the cost of a prescription. **Key target applications for diagnosis include diabetes, drug targeting, cancer detection and health monitoring (both of potentially threatening conditions such as heart problems and of 'wellness' functioning in performance sports).** Early applications would be single diagnosis, with multi-diagnostic functionality and improvements in device mobility following at a later stage.

The action group drew on the data supplied by FreshMinds and their own knowledge of the current prescription market (there are currently 10 billion prescriptions annually worldwide at a cost of \$1–50) to estimate the size of the

Table 2. Market estimates for three-dimensional microstructured materials

	Investment costs – three R&D phases plus one-off pre-production costs							
	Phase 1 Initial investment (duration)	Phase 2 (duration)	Phase 3 (duration)	Pre-production (duration)	Total investment cost (total duration)	Value of UK share of market	World market	UK share
Best guess of UK market size	\$100 million (4 years)	\$80 million (3 years)	\$200 million (3 years)	\$200 million (2 years)	\$580 million (12 years)	\$2 billion	\$10 billion	20%
Optimistic market size (20% likelihood)						\$7.5 billion	\$30 billion	25%

market for a 'gold standard' multi-diagnostic LoC at \$100 billion in 10 years' time. The group noted that the combined diagnostic/therapeutic market could eventually be an order of magnitude larger, but so too would the costs of clinical trials (which would also delay deployment), and so did not consider this market further. The group's best guess was that the UK could capture 5% (\$5 billion) of the broad LoC market, for a total investment of \$570 million.

The group estimated a 20% chance of the market being five times as large and the UK capturing 20% of it – a market share value of \$100 billion. The relatively low-cost initial three-year research stage would be focused on proof of concept for a single diagnostic test, followed by a second three-year research phase to develop multiple diagnostics. Manufacturing processes would be developed in the third phase. The high pre-production costs include setting up a factory and production line, which would need to be undertaken fast (within a year) to capture market share.

The chance of a very high potential return, even though unlikely, together with the fact that a final commitment to the high pre-production costs can be deferred for several years make the low initial investment in this proposal an attractive, though risky, proposition.

Technologies

Micro and nano fabrication

The fabrication of three-dimensional microstructured materials is a platform technology for a range of applications including those identified above. Broadly speaking there are two approaches: top-down, using lithography and/or laser ablation to etch out the device; or bottom-up, assembling it from preformed functional units. Although at present these two approaches are distinct, the group considered that ongoing development of both was essential to achieve a converged capability offering fully flexible manufacture of hybrid structures. For example, lithography patterning might be used to create a structure into which high-value add-ins such as nonlinear components would be inserted using assembly manipulation techniques. In the near term, assembly is likely to be carried out using optical tweezers so units will need to be amenable to manipulation by laser beams. In the longer term, and for assembly on a nanometer scale, units would need to be self-assembling.

The key advantage that new patterning techniques such as two-photon fabrication and holographic lithography offer over existing fabrication technologies is operation in three dimensions. These techniques have been demonstrated in the laboratory but mass production will require development of automated manufacturing methods that do not require expert operators.

Table 3. Market estimates for integrated photonic LoC

	Investment costs – three R&D phases plus one-off pre-production costs					Value of UK share of market	World market	UK share
	Phase 1 Initial investment (duration)	Phase 2 (duration)	Phase 3 (duration)	Pre-production (duration)	Total investment cost (total duration)			
Best guess of UK market size	\$15 million (3 years)	\$45 million (3 years)	\$10 million (2 years)	\$500 million (1 year)	\$570 million (9 years)	\$5 billion	\$100 billion	5%
Optimistic market size (20% likelihood)						\$100 billion	\$500 billion	20%

Critical issues include:

- multibeam parallelisation – to deliver high-throughput speed in both patterning and assembly
- integration of functional prefabricated components into a three-dimensional structure
- patternable materials development: in particular addressing the problem of junctions between different types of base materials for structures made of multiple materials
- high-volume, low-cost manufacturing control and integration processes.

Integrated photonic LoC

At present manipulation and selection in LoCs relies on a limited range of physical and electromigration effects (although the data output is often optical). In the proposed photonic LoC the light is used for new, more specific, diagnostics at single-molecule level, and for sensitive nonlinear techniques (requiring confinement of the light and very short pulses). Light is also used for direct selective manipulation using optical tweezer field-gradient effects.

Key elements of any LoC device are:

- sampling
- sorting/selection
- analysis
- ‘enabling’ functionality.

There are a number of alternative techniques that might deliver the first three of these. Many involve near field effects, so there is some overlap here with the ‘Inside the wavelength: electromagnetics in the near field’ topic. A development path may only need one of each rather than all the options shown on the technology timeline. **The critical technologies are some of the ‘enabling’ ones:**

- **microfluidics: surface control, fabrication, and spatial resolution**
- **laser sources: low-cost tuneable lasers especially at visible and ultraviolet frequencies**
- **detection: on-chip imaging, probably integrating a number of modalities.**

Integration of fluidics and optics into hybrid chips is crucial, as is materials development. To be of use, test results will need interpreting: research will be needed to build up a databank of responses to enable this to be automated, especially in widespread low-end applications such as health testing. The action group envisaged the degree of subjective interpretation required falling off quite steeply with time, with ease of use growing more slowly (and costs falling). As with all data-intensive applications, software development for both analysis and user interfaces is important.

Key technologies for both micro and nano fabrication and integrated photonic LoC are cheap compact lasers with total beam control (shaping, pulses, tuning).

The way forward

The UK could reap rich rewards in the two broad areas of:

- **laser micromachining, driven by demands for ever-smaller and cheaper devices**
- **integrated photonic lab-on-a-chip (LoC), driven by demands for cheap multi-diagnostics particularly but not solely in healthcare.**

The combined potential rewards for the UK from these areas could be around \$7 billion. The market size for the integrated photonic LoC is very uncertain, but offers a small chance of very high returns. To seize these opportunities, an ambitious visionary target is needed; with markets being so young we should not be overly constrained by the current industry position.

The UK has a strong science base in this area and for a relatively small initial investment could maintain this position and keep its options open with respect to these markets, both of which would require more substantial investment at the later stages of R&D and pre-production.

In addition to the two areas identified above, there is a wide range of potential uses of the underpinning technologies in other applications. There are many basic science questions to

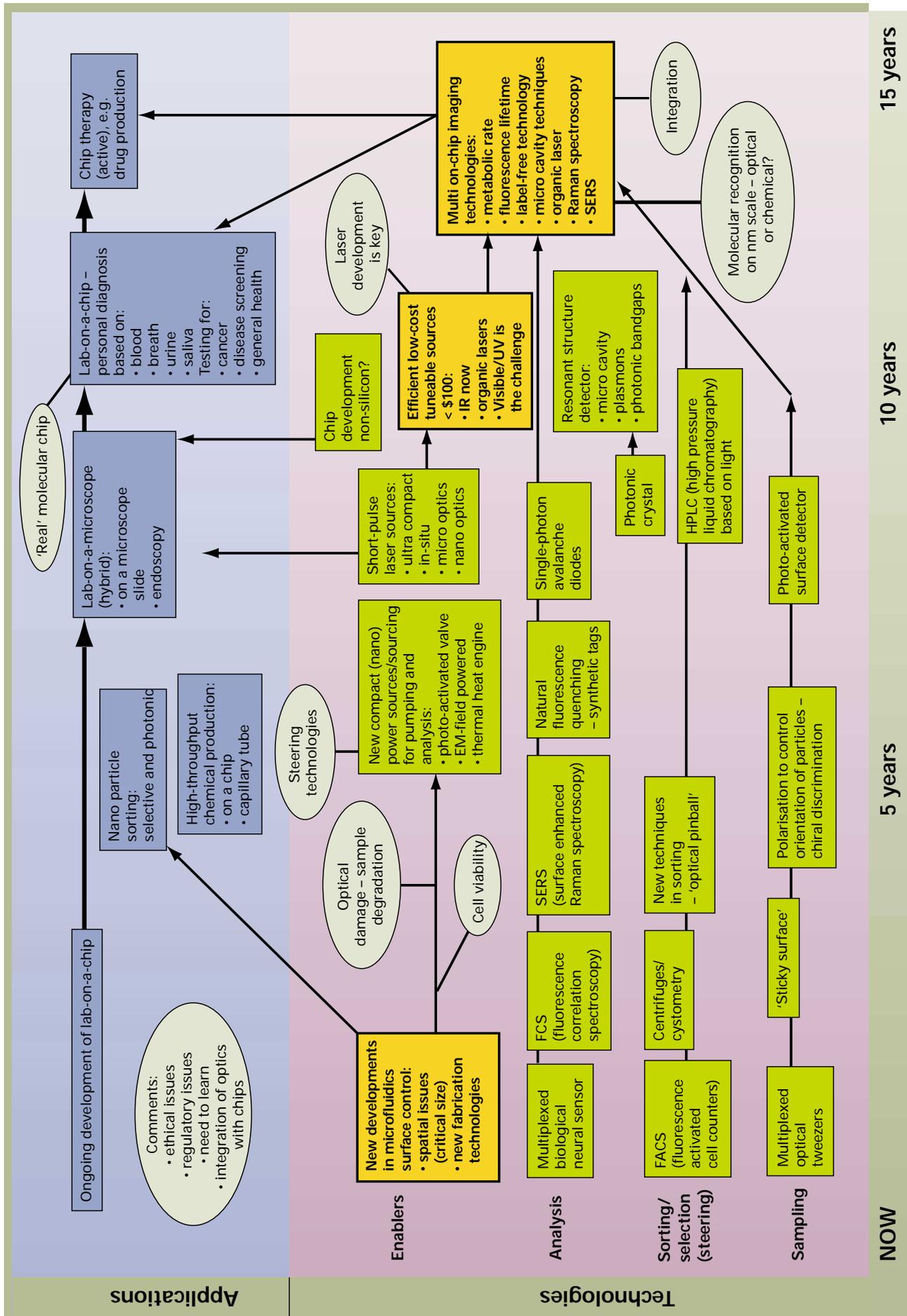


Figure 3. Photonics at the molecular level: technology timeline for integrated photonic LoC (key steps shown in orange)

answer as well as the manufacturing challenges. It is important to co-ordinate a multidisciplinary effort: for the LoC, close involvement of biological and medical scientists is essential. All these factors indicate that support should form part of a national photonics road map, building a strategy for photonics across all areas (that is, combining with the 'Switching to light: all-optical data handling' topic recommendations).

This opportunity, among others, will be considered by the DTI Electronics team's newly formed Photonics Strategy Group, which will identify opportunities and challenges for the UK over the next 5–10 years and develop an action plan to exploit the sector. The team is also working to bring together key players to start a national Photonics network along the lines of the successful Fuel Cells initiative.

Photonics has also been identified as a potential priority area for a Call in 2004/05 under the new Technology Strategy.

Acknowledgements

We would like to thank all members of the action group who gave so generously of their time and expertise.

Professor Donal Bradley, Imperial College London

Nathan Davies, EPSRC

Professor Kishan Dholakia, St Andrews University

Michael Dunn, The Wellcome Trust

Professor Sir Richard Friend, Cambridge University

Dr Clive Hayter, EPSRC

David Hull, DSTL

Dr Andrew Kearsley, Oxford Lasers Ltd

Professor Thomas Krauss, St Andrews University

Dr Coulton Legge, GlaxoSmithKline

Dr Tom McLean, Avecia

David Robbins, Centre of Excellence for Nanotechnology, Micro and Photonic Systems

Dr Shiv Sharma, Amersham plc

Professor Wilson Sibbett, St Andrews University

Professor Andrew Turberfield, Oxford University

State of the science review authors: Professor Kishan Dholakia and Dr David McGloin, St Andrews University.

Inside the wavelength: electromagnetics in the near field



Summary

All Foresight projects seek to explore and establish best practice for science futures work. To this end, we sought a balance between topics defined by application or market and those defined by the underlying science. This topic is of the latter type and consequently its application areas are more diverse. The near field is the confined non-propagating part of an electromagnetic field (at any frequency) that decays away exponentially from a surface, within a distance of about a wavelength. The recent UK-led discovery of 'metamaterials' (composite artificial materials) will allow manipulation and use of the near field in ways not previously possible.

Near field technologies are critical to developing smart antennas and integrated radio frequency infrastructure and circuitry. The UK has a strong industry presence in this

sector and there is already much short-term incremental development. Long-term goals include wearable antennas, very accurate beam control, integrated broadband antennas and low SAR (specific absorption rate) antennas.

Metamaterials are opening up exciting possibilities in other areas, such as sub-wavelength resolution imaging using 'superlenses' especially in MRI (magnetic resonance imaging). **As yet there are no obvious single applications that alone would be of sufficient potential to justify focused investment. More basic research is needed to explore the full potential of metamaterials.**

Introduction

In general, at whatever frequency in the spectrum, it is the propagating wave part of the electromagnetic field that is exploited – whether that be radio waves transmitting information, visible light providing illumination or laser beams cutting materials. The full electromagnetic field, however, comprises both these travelling waves and a non-propagating component that decays away very rapidly from emitting surfaces. Since it is negligible except within about a wavelength of the surface, it is called the near field, although the distance it extends over can be many metres for low-frequency radio waves. **Newly discovered metamaterials offer prospects for manipulation of the near field across a wide range of frequencies and many diverse applications.**

Controlling the near field would enable many advances in efficient radio communications: reductions in interference, losses, energy consumption and absorption of power by human tissue. Over smaller distances, local

communications (for example, between smart devices within the home) might be carried entirely within the near field.

In addition to being highly localised and non-propagating, the near field can vary on scales much smaller than the wavelength of the associated propagating wave. If the near field could be imaged, detail on sub-wavelength scales could be resolved – detail that cannot be seen with propagating waves, whose resolution is limited by their wavelength. Metamaterials are a broad class of artificially created materials with electromagnetic properties beyond any found in nature. Some metamaterials have negative refractive indices, which means that they bend light in the opposite (negative) direction to the bending caused by all naturally occurring materials. This property opens up the possibility of imaging the near field by creating a ‘superlens’ with a negative refractive index to capture and image the information in the near field.

This could be of use in MRI where improving resolution is currently achieved by increasing the strength of the background magnetic field. This reduces the wavelength of the imaged signal but high field magnets are expensive to make and cumbersome to work with. As research into negative index materials continues, there are likely to be other potential applications for a superlens.

At metal surfaces and for frequencies in the optical range the near field interacts with the conductance electrons in the metal to form a ‘surface plasmon’. In metal foils patterned with holes, surface plasmons can cause radiation of a much longer wavelength than the dimensions of the holes to be transmitted through them, something that at first glance seems counterintuitive. Surface plasmons can contain localised regions of very high field density, offering prospects that include: holding (bio)molecules in position for individual testing; on-chip communications; and powering nonlinear optical effects (such as are needed in applications like fast optical switches).

The action group considered three areas of

potential application of near field effects: **antennas and electromagnetic interference (EMI) control; MRI near field imaging; and local near field communications and optical bio-sensing.**

Antennas and electromagnetic interference control

Key drivers

As described under ‘Switching to light: all-optical data handling’, global data transmission demands are growing and, whilst rates of growth may fluctuate, the trend is likely to continue upwards. This is a key driver for both fixed-line and mobile communications systems. Wireless traffic is growing and in the future may well include increasing amounts of inter-device communication between ever more intelligent devices, such as smart home appliances, car navigation systems and trackers for radio frequency identity (RFID) tagged objects.

Demand for more bandwidth will increase pressure for more efficient use of the radio frequency (RF) spectrum, for example, through better beam control or by using confined near field communications.

Consumer expectations create strong drivers for reducing the cost, size and weight of devices. At present health concerns over SAR are not a major driver – consumers show no preference for low-SAR models when buying phones – so producers have little motivation to develop low-SAR devices. Were public opinion or regulations to change, health concerns could rapidly become important. This possibility cannot be ruled out, especially as the network becomes more pervasive, and would be a major driver for very low-SAR equipment.

Markets and applications

The antenna market is very cost-driven and the price attrition that has seen unit costs for mobile-handset antennas drop from \$1 four years ago to \$0.30 today is likely to continue. There is a wide range of product improvements that could be delivered if the market was prepared to pay for them. The group considered

the markets for some examples. The UK has a strong presence in these markets (principally through Filtronic, along with smaller companies including Antenova and Sarantel).

Most promising of these is **base station RF infrastructure**. Despite the decline in this market over the last few years due to lack of demand for high-speed services such as third-generation communications (3G), the action group expected the market to start to grow again shortly and estimated that in five or six years' time it would have a value of \$140 billion. **The UK is in a strong position to capture 30% of this market (\$42 billion)**, although taking into account the high relative costs of production in this industry results in an estimated gross margin value of \$7 billion. Total costs of R&D were estimated at \$180 million, with the bulk of this coming at the pre-production stage. Phase one of the R&D would demonstrate the basic concept; phase two would involve demonstrator and original equipment manufacturer (OEM) discussion to ensure product match, and phase three would cover pre-production prototyping, tooling up and OEM evaluation. The UK's strong market position and the large potential market make this an attractive proposal from a traditional discounted cash flow analysis, as well as from a real options viewpoint.

The action group also considered an **RF 'front end' for mobile terminals**: integrated RF

circuitry including the antenna and incorporating Bluetooth, wi-fi and similar. This product could be used in a wide range of devices and the group estimated a global market value of \$30 billion in five years' time, of which the UK might capture 20% – \$6 billion – with a gross margin value of \$1.5 billion once the high production costs are subtracted. Unlike the RF base station infrastructure, this product may require a silicon foundry, so is unlikely to happen in the UK unless foundries are built. The high costs of these are included in the investment costs at the pre-production stage in Table 5, and make this a much less attractive proposal than the base station, though still profitable.

Third, the group looked at a compact **cheap dielectric loaded antenna with very low SAR** for use in mobile phones, which they estimated could be brought to market in around 5 years. Much of the basic research has been done: the main task is cheap mass production. The UK's strong position in the market means it might capture 30% of a market valued at \$150 million. Capturing more than 40% was considered very unlikely due to the need for the major handset manufacturers to keep competition in the supply base. The higher data transmission rates of 3G (and beyond) may boost the appeal of low-SAR antennas, which, all else being equal, are clearly always preferable.

Table 4. Market estimates for base station RF infrastructure

	Investment costs – three R&D phases plus one-off pre-production costs					Value of UK share of market	World market	UK share
	Phase 1 Initial investment (duration)	Phase 2 (duration)	Phase 3 (duration)	Pre-production (duration)	Total investment cost (total duration)			
Best guess of UK market size	\$15 million (1.5 years)	\$25 million (1 year)	\$40 million (1.5 years)	\$100 million (1.5 years)	\$180 million (5.5 years)	\$42 billion	\$140 billion	30%
Optimistic market size (20% likelihood)						\$66 billion	\$190 billion	35%

Table 5. Market estimates for RF ‘front end’ for mobile terminals

	Investment costs – three R&D phases plus one-off pre-production costs					Value of UK share of market	World market	UK share
	Phase 1 Initial investment (duration)	Phase 2 (duration)	Phase 3 (duration)	Pre-production (duration)	Total investment cost (total duration)			
Best guess of UK market size	\$15 million (1.5 years)	\$15 million (1 year)	\$25 million (1.5 years)	\$1 billion (1.5 years)	\$1.1 million (5.5 years)	\$6 billion	\$30 billion	20%
Optimistic market size (20% likelihood)						\$10 billion	\$40 billion	25%

Technologies

Much of the basic R&D has been achieved for short-term products.

Key development areas include:

- low-loss materials – to reduce losses by half to under 25%
- wide bandwidth (since there is a fundamental tension between this and low losses, effective wide band may need to be achieved by hopping between many narrow bands)
- high isolation – controlling cross-channel interference both among classes of devices and between different types of device
- integrated RF circuits
- adaptive materials
- flexible lightweight high-dielectrics
- low SAR (perhaps 20 times better than present) through directional control of radiation beams and lower power.

If SAR becomes a more serious issue, better models of absorption by tissue and improved SAR verification technology will be needed.

In the longer term, the group anticipated antennas becoming small and lightweight enough to be wearable, for example, integrated into clothing. Similar trends towards tiny low power base stations might open the way for smart houses with pico-cell base stations providing a totally networked environment with no increase in radiation levels.

Magnetic resonance imaging (MRI) near field imaging

Key drivers

As explained more fully in ‘Picturing people: non-intrusive imaging’, increasing expectations for healthcare are expected to be a major driver in expanding medical markets in the future. **Imaging plays a key role in detection and treatment of disease and there is strong demand for improvements in functionality, safety, efficiency, access and ease of use.** MRI is one of the safest imaging modalities currently in use. Improving its resolution, and reducing the cost and size of machines, would strengthen the relative position of MRI in the medical imaging market. In the long term, metamaterials may enable MRI machines to be sufficiently cheap and portable that they could compete with ultrasound and x-rays in the ‘mass market’ of primary healthcare-centre imaging, rather than remaining the high-end specialist modality they are at present.

Markets and applications

A particularly appealing feature of MRI as an imaging modality is its safety: unlike x-rays, positron emission tomography (PET) or single-photon computerised tomography (SPECT), it does not involve ionising radiation. However, MRI machines have relatively poor resolution and are costly and bulky. The last two are mainly due to the magnets needed to produce the high magnetic fields that create the conditions for

resonance, and the associated screening needed to contain and isolate these fields. Resolution can be improved by using higher field strengths, which requires even more expensive magnets. Specificity may be enhanced by the use of smart contrast agents, as described more fully in the 'Picturing people: non-intrusive imaging' topic.

Negative refractive index metamaterials offer the prospect of improving MRI resolution by imaging the near field part of the radio frequency signal, using a 'superlens', and of controlling the electromagnetic fields so that they are targeted where wanted and screened from elsewhere. Machines could then be less bulky and would allow surgeons to perform in-situ operations. In the longer term, metamaterials developments may facilitate portable MRI machines – maybe even a stethoscope-style device.

The action group considered the market for an MRI multifunctional superlens. This product would be an enhancement to future high resolution MRI machines (or possibly retrofitted to existing machines). The cost of the enhancement would be offset by reductions in high field magnet costs, and by gains in cost efficiency: superlenses offer the possibility of much faster parallel data acquisition, thus speeding up the scanning throughput rate. The UK has little presence in the MRI hardware market, except in magnets, so the market considered was just that for the superlens itself. This was estimated at \$100 million, with the UK able to capture 20%. Consideration of the costs of development, in particular the establishment of high-volume manufacturing processes for the metamaterials components, led to the conclusion that, despite the exciting science, there was not a clearly defined significant market opportunity for this particular application.

Developing a superlens remains an important research challenge and, in the longer term, metamaterials may provide the means to produce portable MRI devices that could command a much larger market than enhancements to specialist high-end machines.

The group also considered the markets for replacing the current copper screening of dedicated MRI rooms with metamaterials. Their

evaluation indicated that the small screening market value would not cover the costs of developing the necessary metamaterials, even though these would only need to screen the specific frequencies used in MRI. Materials providing 'broadband' screening across a wide range of frequencies would have more widespread applications, including military stealth ones. The group concluded that, despite the absence of a single large-market application for metamaterials at present, there was a large number of niche applications based on essentially the same underlying technology, and that more applications were likely to emerge as the research field became more mature.

Technologies

A key technology challenge is manufacture of the metamaterials components of superlenses. Materials expertise from those involved in manufacture of similarly scaled devices, such as capacitors, may be the route to a solution. Mass production would clearly be needed for commercial production, but significantly more efficient methods are also needed to facilitate further R&D into superlens applications and into the general theory of superlensing itself, which remains a topic of much fundamental research interest.

In addition to the manufacturing challenge, the potential applications in lenses and screening (such as, for example, a portable MRI 'stethoscope') will require metamaterials that are low-loss (a tenfold improvement over current performance), lightweight and flexible.

Local near field communications and optical bio-sensing

Key drivers

Depending on the radio frequency being used, local communications – over distances of up to several metres – cannot avoid being in the near field. In addition to offering a new channel of communication, use of the near field also carries the advantage of being very localised, making it easy, for example, to ensure that your smart fridge does not pick up your neighbour's instructions.

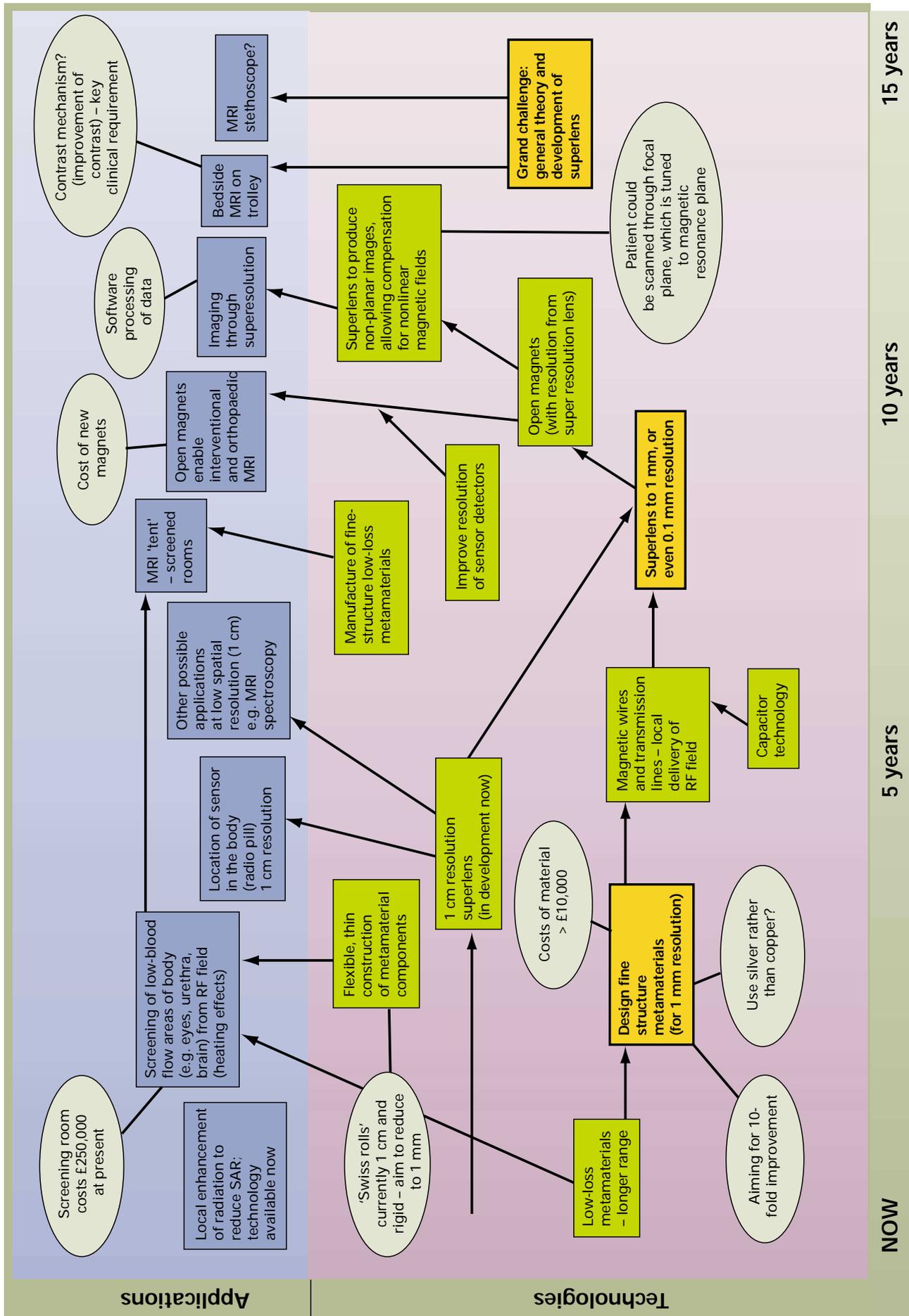


Figure 5. Electromagnetics in the near field: technology timeline for MRI near field imaging (key steps shown in orange)

The previous section on the 'Manufacturing with light: photonics at the molecular level' topic described drivers towards improved bio-molecular testing capabilities in greater detail. Demand for genetic testing – identification of the sequences of bases in DNA – is expected to increase, for health treatment, for private or insurance-related screening and in pharmaceutical drug development and testing. This will drive the development of faster techniques, a demand that could be met by a number of different technologies.

Markets and applications

As noted in the 'Manufacturing with light: photonics at the molecular level' topic, there are a number of near field techniques that could be incorporated into an integrated photonic LoC for bio-sensing. The action group for the 'Inside the wavelength: electromagnetics in the near field' topic considered the specific application of **high-throughput DNA molecular screening**.

Although there are competing technologies (including the polymerase chain-reaction methods widely used today), the group felt that near field technologies might offer a promising solution in which the DNA base molecules to be tested would be captured and localised by the near field on metal sheets patterned with tiny holes. The molecules would then be identified using scanning near field optical microscope (SNOM) probes, effectively performing single-molecule spectroscopy at each test site. There are considerable challenges to development, some of which are not electromagnetic, including: devising a way of streaming the DNA through the metal foil; identifying accurate test reagents and establishing the near field signal detection process. The complexity of the technical challenges and the number of competing technologies make it difficult to estimate markets with any degree of confidence.

The action group also considered **local near field communications** over small distances such as those covered by Bluetooth and wi-fi. This would be an adaptive wireless personal grid, enabling inter-device communications between personal electronic devices and also potentially your smart appliances at home. However, uncertainty over

competing technologies in this market led to the conclusion that it was difficult to assess the scale of this opportunity at present.

Probably beyond the timescale of this project, and too far for the group to feel comfortable about making any reasoned predictions of market size, the action group considered the potential uses of a brain reader, using either the near field generated outside the head by the electrical activity inside, or MRI-like techniques. Such a device would clearly be of great benefit to cognitive scientists (and was in fact identified as such by the Foresight Cognitive Systems project). Measuring brain activity could also be of great use in monitoring and treating mental illness. If signal activity could be reliably mapped to intentions or actions, brain reading could have security uses, or be used to help understand and improve the way the brain learns. Significant ethical issues are raised by these possibilities, and in the absence of any clear road to market they were deemed not to offer a clear exploitation opportunity.

Technologies

The technology timeline shows the range of applications that might make use of near field effects for local (short-range) communications and optical bio-sensing.

Key technological challenges include:

- accurate fabrication of free-standing holey metal foils
- development of a near field–far field conversion device
- controlled highly localised field enhancements to power nonlinear optics at low-input powers
- near field photochemistry – tuneable lasers are an important enabler
- high frequency magnetics.

A local wireless near field grid will in addition need protocols, software and near field containment, using metamaterials. Fast DNA base readers will also require the development of nano-fluid technology for fast molecular streaming.

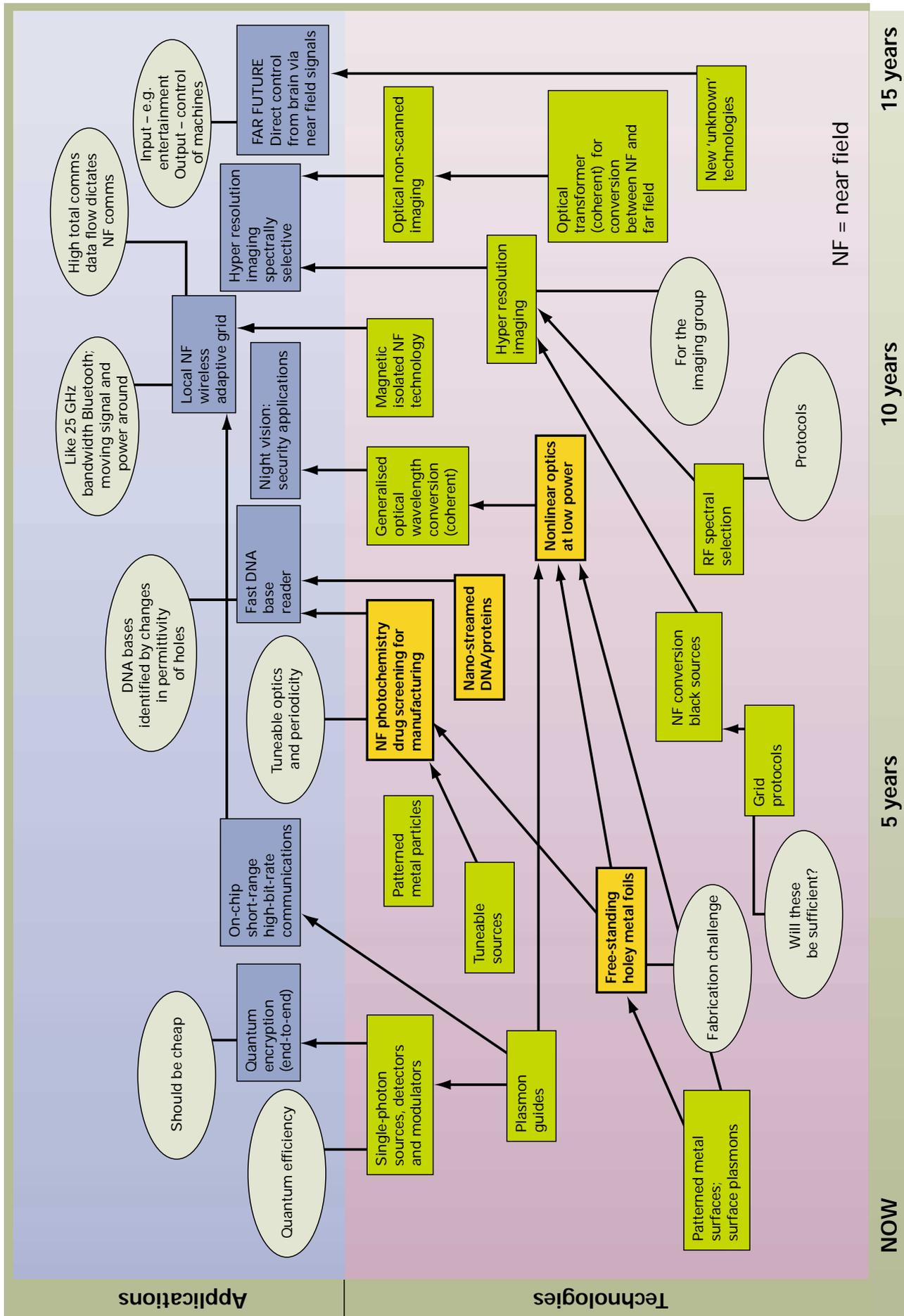


Figure 6. Electromagnetics in the near field: technology timeline for local near field communications and optical bio-sensing (key steps shown in orange)

The way forward

Near field technologies are essential to integrated radio frequency infrastructure and circuitry and smart antennas. The UK has a strong industry presence in this sector and there is already much short-term incremental development. Measures that would support this industry's growth include:

- facilitating and encouraging industry collaboration, in particular establishing clear Intellectual Property (IP) exchange/protection rules
- ensuring an adequate UK skills base through training and education initiatives.

Metamaterials could facilitate a step-change in technological capabilities across a wide swathe of the spectrum and unlock the potential of the near field in many application areas. They could underpin the next generation of technology in areas such as antennas, medical imaging equipment, stealth capabilities, local communications networks and bio-assays.

Because of the novelty of the science and the uncertainty over competing against more established technologies, there is no clear path to a single, large, long-term market, although there are many potential niches or very long-term markets.

The many and widespread potential opportunities do, however, strongly support continued investment in broad research in this area. Bringing together a wide range of disciplines from business and academia is very important, particularly to draw in manufacturing and material expertise. Collaboration offers the best chance of understanding where these exciting technologies can be exploited to meet application demands.

The MOD has a user requirement for metamaterials in a wide range of sensing applications, and will work together with EPSRC and relevant university departments to consider opportunities for joint funding of proposals under the Joint Grant Scheme. The MOD will continue to monitor this area for

its potential defence implications and the need for larger collaborative programmes in the future.

Acknowledgements

We would like to thank all members of the action group who gave so generously of their time and expertise.

Professor Anthony Barker, Royal Hallamshire Hospital, Sheffield

Dr John Causebrook, Consultant to Vodafone Group

Dr Bob Clarke, NPL

Mr John Griffin, BAE systems

Professor John Griffiths, St Georges Hospital Medical School, London

Dr Tony Holden, Consultant Physicist

Dr Carl Norman, Toshiba Research Europe Ltd

Miss Jane Nicholson, EPSRC

Professor John Pendry, Imperial College London

Dr Peter Radley, Antenova Ltd

Dr Sean Ralph, DSTL

Professor Roy Sambles, Exeter University

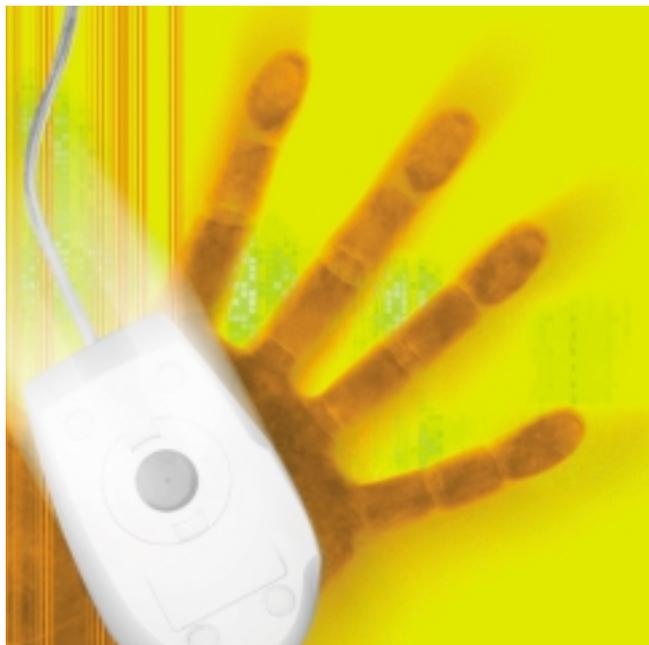
Professor Christopher Snowden, Filtronic plc

Dr Zhou Wang, Ofcom

State of the science review author:

Dr Tony Holden

Picturing people: non-intrusive imaging



Summary

Novel non-intrusive imaging techniques have applications in both healthcare and security. In the medical imaging market, value is expected to continue to move away from the hardware, where the UK is weak, to the smart agent sector and to imaging and data-handling software. Smart (sophisticated contrast) agents are particles or molecules that can be used to tag indicators of disease so that these show up when the patient is imaged. Smart agents offer the prospect of high specificity molecular imaging for the early and non-intrusive detection of diseases like cancer, and vascular, neurodegenerative and neurological conditions.

The UK could capture a \$6 billion share of the market for smart agents for medical imaging. A critical step in doing so is identifying new reagents with new functionality.

Detection of weapons and explosives at a distance, using safe reliable and cheap technology, is a growing requirement in today's world. The UK is in a leading position in

developing security imaging using combinations of frequencies from millimetre waves through terahertz (THz) to infrared. **A key enabler for UK businesses to capture a \$0.4 billion share of the market would be the provision of a national foundry to enable companies to prototype their inventions fast and within a secure IP environment.**

Introduction

Most of the electromagnetic spectrum is used in some way for imaging. Detecting the radiation emitted by objects, or reflected or transmitted by them when illuminated, can provide a wealth of information about the object (such as what it is made of, what lies inside it), in addition to an image of its external surface. **Different frequencies provide different information, so the long-term ideal would be 'hyperspectral' imaging in which all information at all frequencies is captured and blended for display – all at once.** An intermediate step would be the integration of multiple imaging modes to provide a fuller 'picture' than that from a single imager.

In both medical and security imaging there is a need for less-intrusive imaging. For medical imaging this means making equipment less physically intrusive upon a patient, and using safer types or doses of radiation. At frequencies above ultraviolet the energies of the individual photons (light 'particles') are sufficient to ionise (that is, remove negatively charged electrons from) atoms or molecules. In living tissues, this disrupts the electro-biochemistry of cells and can damage them and lead to an increased risk of cancer. Consequently, all else being equal, non-ionising modalities are to be preferred. The positive features of x-ray imaging and other ionising modalities mean that they are unlikely to be replaced in the foreseeable future for specific scans, but MRI and ultrasound offer prospects for extended functional imaging over long time

periods, for example, throughout an operation. Ultrasound is of course not an electromagnetic spectrum technology, although it has to be considered as a competing technology in the marketplace.

Security scanning of people cannot use ionising radiation for safety reasons (x-ray scanners at airports are used only for baggage). Less-intrusive imaging has obvious advantages in being more covert, and less disruptive to passengers at airports, for example. **An exciting new area with great promise for security imaging is THz radiation, which lies between microwaves and visible light and can provide spectroscopic information to identify substances, as well as images of concealed items.** Use of the THz part of the spectrum has been hampered by the absence of cheap sources and efficient detectors. Recent breakthroughs, led by the UK, are now opening up opportunities for THz applications, which may well extend beyond the security sector.

Medical imaging

Key drivers

Greater demand for healthcare, particularly for an increasingly aged, and affluent, population, is widely recognised as a critical driver in society.

Within the drive towards better healthcare there are a number of broad trends. **The desire to minimise the negative side-effects of healthcare, and the growing requirement to image patients for extended periods during treatment and screen for predisposition to disease, provide strong motivation towards less-invasive imaging methods.** Surgery carries its own set of risks, particularly of infection. Keyhole surgery has replaced many major surgical interventions; improved imaging offers the prospect of reducing the need for biopsies and other investigative operations.

Ionising radiation (x-rays, PET, SPECT and gamma ray scans) cause damage to cells that can lead to cancers. There is thus a drive towards using non-ionising imaging modalities, such as MRI, where possible, and reducing dosages where there is no alternative to ionising imaging modalities.

In seeking to improve treatment capability, a high priority is placed on combating the big killers, including oncological, vascular, neurodegenerative and neurological diseases. High specificity and high sensitivity imaging plays a central role in the early detection of disease and in monitoring the effects of therapy. In due course it could also become integrated into highly controlled guided therapy systems using feedback from real-time diagnostic monitoring. It might also find a market for mental state monitoring of the growing number of people who suffer depression at some stage of their life.

Another key driver in healthcare is equality of access. Many advanced treatments and diagnostic tools are currently only available at specialist centres. This provides a drive to cheaper, more compact imaging devices that do not require a specialist to operate or interpret them.

The action group considered that within the context of non-intrusive imaging, the drivers in healthcare led towards two key market areas: **high specificity and molecular imaging** for disease detection by specialists; and **low-cost flexible imaging** devices for primary healthcare centres.

High specificity and molecular imaging

Markets and applications

High specificity imaging plays a central role in the early detection of diseases such as cancer by identifying molecular signals of disease.

The development of continuous monitoring would enable the effects of therapy, or a patient's mental state, to be tracked, and drug type and dosage adjusted accordingly. In the longer term, diagnostics and treatment could be integrated into therapy systems in which feedback from real-time diagnostic monitoring would control highly-personalised therapy.

The most promising way of delivering high specificity non-intrusive imaging lies in the use of smart agents with an imaging modality such as MRI, PET or x-rays. Smart (sophisticated contrast) agents are particles or

molecules that enable specific indicators of disease to show up when the patient is imaged. Contrast agents are passive tags that can be seen at all times, whereas smart agents have active features – for example, they may only ‘switch on’ once attached to the target. Long-term goals for very smart agents involve active transmission of information rather than simple imaging of location. Although improvements in imaging hardware alone might deliver improved specificity, for example, better tissue recognition, imaging at the molecular level is likely to require smart tagging for the foreseeable future.

The principal components of a smart agent high specificity imaging system are: the imaging hardware; the data analysis software; and the tagging agents through which indicators of disease are identified. At present, about 60% of the value of the market lies in the hardware, but the value of this sector is declining relative to agents and data analysis. The group estimated that in 15 years’ time 50% of the value of the overall market would lie in smart agents.

In assessing the market for smart agents, the action group considered that detection of cancer, vascular and neurodegenerative/neurological diseases would form the major part of the market. Their ‘best guess’ estimate was for a combined market value of \$25 billion in around 15 years’ time, with the relative sizes of the markets for these three diseases being 40% oncology, 30% vascular and

30% neurodegenerative/neurological. The group noted that, although detection of diabetes was also a potential application, alternative detection technologies were already established so the prospects for smart agents were less certain in the face of such competition. **The UK has a strong presence in the smart agent market (Amersham plc) so the group estimated that the UK might expect to take 25–35% of this market** (if Amersham plc remain based in this country).

The initial stage of the R&D process is relatively long, probably academic rather than industrial, and will involve trying a number of avenues to achieve proof of concept identification of a new agent with novel functionality. This would be followed by a short commercial proof of concept phase, which may include adding new functional components into the imaging equipment to maximise the efficacy of the new agent. The key milestone at the end of a lengthy (about 8 years) phase three is approval from the US Federal Drugs Agency (since around 45% of the market is in the US), although European Union approval is also important. One-off manufacturing start-up costs are relatively low because the production processes established during development are likely to be adequate for the production volumes. The R&D process is the same for each disease although initial investment costs will be higher for neurological agents because of the extra difficulties associated with transmission across the blood–brain barrier.

Table 6. Market estimates for smart agents

	Investment costs – three R&D phases plus one-off pre-production costs					Value of UK share of market	World market	UK share
	Phase 1 Initial investment (duration)	Phase 2 (duration)	Phase 3 (duration)	Pre-production (duration)	Total investment cost (total duration)			
Best guess of UK market size	\$160 million (5 years)	\$50 million (2 years)	\$1.2 billion (8 years)	\$75 million (1 year)	\$1.5 billion (16 years)	\$6 billion	\$25 billion	25%
Optimistic market size (20% likelihood)						\$13 billion	\$37 billion	35%

The principal risk to the UK investing in this area is that of GE pulling Amersham plc out of the UK (but the new GE Healthcare business will be headquartered in the UK). Setting that aside, the UK's research and business strengths in this field and the relative confidence of this as a growing market make this a less uncertain proposal than some others considered by the project.

Technologies

Identifying new smart agents with the desired functionality is the key technological development. Passing all the regulatory trials and gaining approval for their use is the most expensive step. In the longer term, development of more generic nanotags with transmission capabilities would permit ever-more intelligent imaging.

Dual modality instruments (such as PET/CT) are available now. Fully multispectral imaging, fusing data from multiple modalities, is a long-term goal. Sophisticated data analysis and fusion software is essential.

Low-cost flexible imaging

Markets and applications

Earlier detection of disease does not depend only on better-quality imaging, it also depends on patient access. Improving the imaging capabilities available at point of entry into the healthcare system would enable doctors to make earlier, more accurate, diagnoses.

The challenges in addressing the primary healthcare-centre imaging market are not about new technologies but about engineering current ones to be cheaper, more compact and easier to use. The size of the market for these devices will depend on a number of other infrastructure enablers including: high-bandwidth telephony for data transmission to and from experts; skills and educational provision at the local level; and clear data protection, and automated decision-making, regimes that are accepted by the public and professionals alike.

The action group agreed that only certain imaging modalities were suitable for moving down the healthcare chain, from specialist centres to all hospitals and/or from them on to primary healthcare centres. The group discounted any significant future market for modalities involving radioactive isotopes in primary healthcare centres on safety/security grounds. It was agreed that the modalities of ultrasound and (digital) x-rays offered the best prospects for meeting the demands of this market in the short term. MRI was thought to be significant in the longer term, but requires more to be done by way of development to meet the specifications of the market. A key requirement is ease of use: if equipment is to become commonplace in primary healthcare centres it must not require a specialist to operate or to interpret the data. Smart software for data and image analysis is thus critical, although this will need to be combined with local training.

Because addressing the production aspects of this market is in the main about refining the engineering of existing products, existing suppliers clearly have a great advantage. The UK has very little presence in this sector and the group concluded that whilst the market was significant (they estimated the size of the digital x-ray market alone for primary healthcare centres at \$45 million in 5 years' time) there was little chance of the UK capturing any worthwhile part of this market. **The UK has strengths in software and image analysis development, which form component parts of the overall market.** The group felt that these offered good entrepreneurial opportunities for small-scale businesses but any such ventures were likely to be bought out by larger overseas equipment manufacturers if successful.

Technologies

As with high resolution high-end imaging, sophisticated data analysis and fusion software is essential for low-end low-cost imaging. Imaging software has in recent years been driven by the entertainments industry: there was no clear consensus on whether

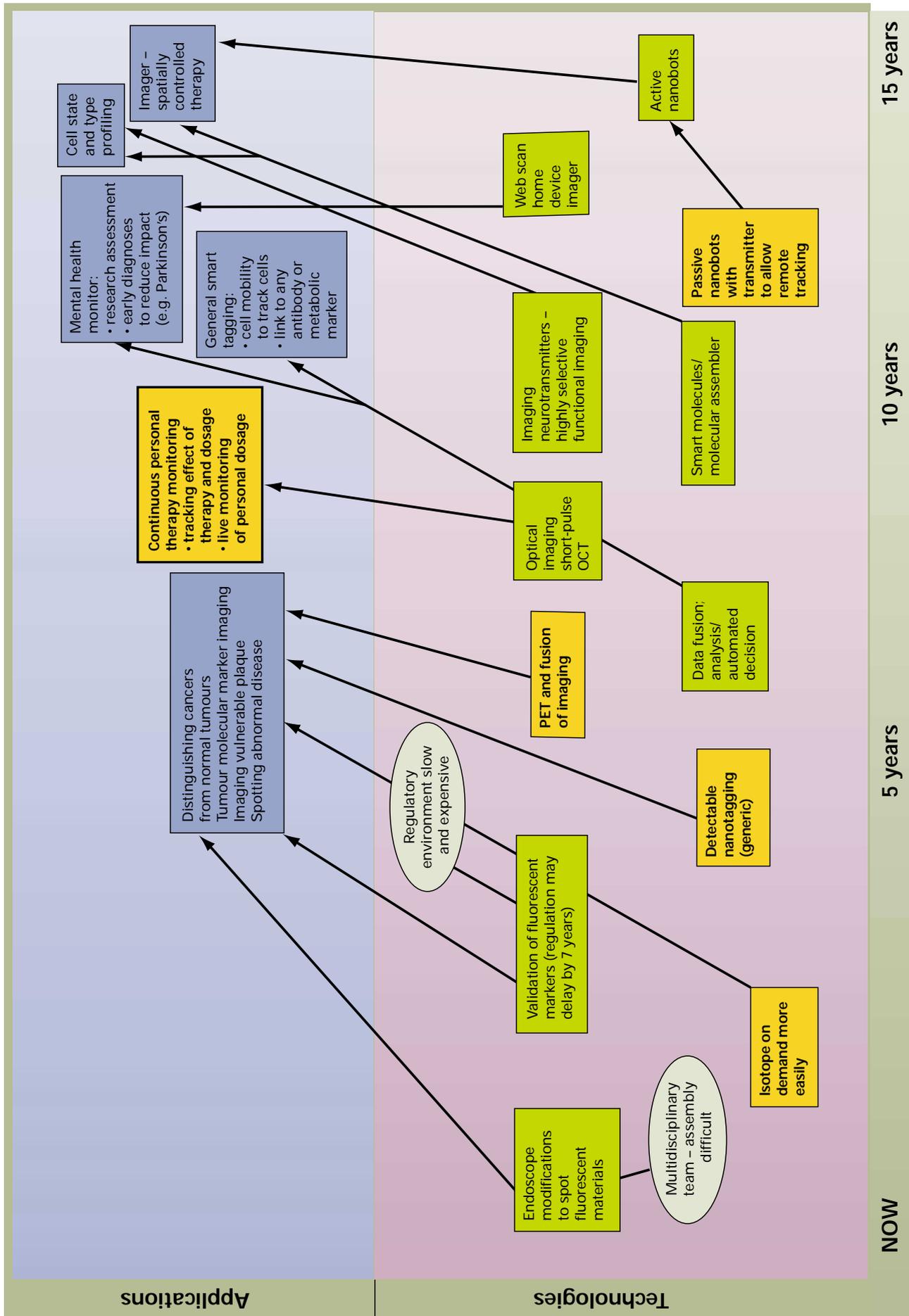


Figure 7. Non-intrusive imaging: technology timelines for high specificity and molecular imaging. (key steps shown in orange)

software developments could be relied upon to keep pace with medical imaging technology without any specific plans or co-ordination. It can be seen from the timeline that many of the key issues for this product are social and economic, not technical.

Security imaging

Key drivers

Following the attacks of September 2001, security spending, particularly on airport screening, rose steeply. Although aviation security spending dropped again the following year, the overall trend is upwards.

With threats from terrorism continuing, both military and civilian security spending are expected to increase significantly over the next 5–10 years. Longer term, it is unclear whether spending will go on increasing if it is not achieving cost-effective improvements in security. Aviation security is likely to remain a key driver for security imaging markets although detection of suicide bombers on the ground could be a growth area if effective remote identification (and containment) became possible.

Higher expectations of personal safety make tackling 'everyday' crime another important driver and new covert imaging techniques are likely to find civilian markets for the detection of weapons, drugs and explosives.

Markets and applications

Many security systems involve imaging of some kind (chemical detection is also a large market), and all imaging modalities used for mass screening of people have to use non-ionising radiation. Within the overall security market there is a wide variety of applications using a range of different types of imaging technology. The biggest market is in the detection of explosives and weapons, at increasingly remote distances, both in airports and at large, where the environment is much less controlled.

The action group considered a number of applications before focussing on a relatively low-cost CCTV-type package for detection at distances of up to 20 m. Looking about 10 years' hence, they estimated the global market for such devices at \$1.5 billion, on the basis of capturing \$1 billion of a \$3.5 billion market in airport security, and a further \$0.5 billion in non-airport security systems. **The UK has a leading research position so the group's best guess was that the UK could capture 25% (\$400 million) of this market.** Depending on the state of global terrorism and public reaction, the group considered that there was a 20% chance of the market being at least \$10 billion and the UK capturing 50% (\$5 billion). It was considered highly unlikely that any non-US country would ever obtain more than 50% of the market.

Table 7. Market estimates for CCTV-type security imager

	Investment costs – three R&D phases plus one-off pre-production costs							
	Phase 1 Initial investment (duration)	Phase 2 (duration)	Phase 3 (duration)	Pre-production (duration)	Total investment cost (total duration)	Value of UK share of market	World market	UK share
Best guess of UK market size	\$50 million (2 years)	\$15 million (1 year)	\$50 million (2 years)	\$30 million (1 year)	\$145 million (6 years)	\$400 million	\$1.5 billion	25%
Optimistic market size (20% likelihood)						\$5 billion	\$10 billion	50%

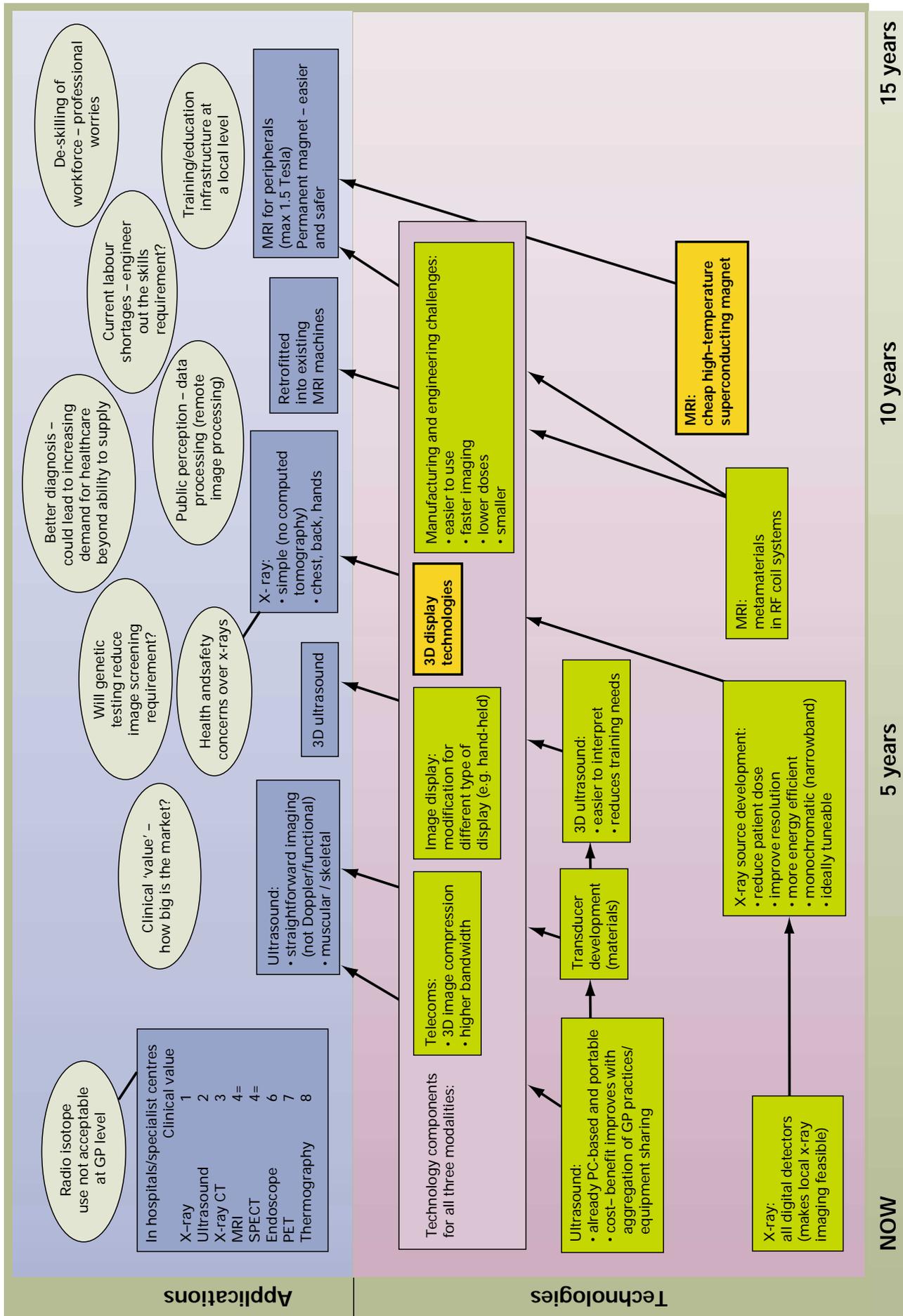


Figure 8. Non-intrusive imaging: technology timeline for low cost flexible imaging (key steps shown in orange)

The first phase of R&D would provide proof of concept for the technology and components. The second would demonstrate commercial viability – integration and manufacture – and the third would produce final prototypes. Pre-production costs depend on whether the UK builds a mass-production foundry: for their ‘best guess’ figure the group assumed some kind of factory share. To capture the optimistic 50% share of the market a dedicated UK foundry would be needed. Compared to some of the other proposals considered by the project, the initial investment costs are higher, with the middle phases being the cheaper ones although it is still an attractive option. To reap big benefits will, however, require both a prototyping and a mass production foundry.

Technologies

There are very many imaging technologies to consider in meeting the needs of security markets, and most are likely to find a use in some particular niche application. For example, vapour spectroscopy could be important for remote detection of volatile substances, and thermal detectors are likely to continue to be used in low-resolution short-range applications.

Even for the entry-level CCTV-imager market there are a number of different specific electromagnetic technologies that could meet the specification for this device. The imaging radiation is likely to be in the millimetre wave to THz to infrared range, where the resolution is good and substances may be identified by spectroscopy. Penetration, particularly in wet weather, can be an issue if these devices are to be used outside.

Technology developments are particularly needed to produce cheap reliable detectors: it is likely that there will be a move away from the current Indium Phosphide (InP) detectors to silicon. Because of this, the group felt that the development of a UK, or EU, silicon R&D foundry to enable rapid prototyping of designs was essential for the UK to build on its presence in this market.

In the longer term, discrete imaging units will be increasingly combined into hybrid systems, possibly using data at many frequencies and

integrated on-chip (at least 20 years out). As with other topics, image analysis and processing software is critical to the development of sophisticated surveillance systems.

The way forward

The UK has the opportunity to develop a significant market share in:

- **smart agents for use in high specificity medical imaging**
- **non-intrusive security imaging using frequencies from millimetre waves through THz to infrared.**

The UK could capture a \$6 billion market in smart agents for disease detection. The UK has the scientific expertise and, in Amersham plc, an industry leader well placed to exploit this opportunity. The challenge is to support UK business to maintain their position and stay in the UK.

A critical step in capturing markets is the identification of new smart agents. To ensure this happens, we need to further develop the excellence of imaging science in the UK and facilitate interdisciplinary research. Support for development advances needs to be well focused, for example, by: setting up a multi-disciplinary research facility located in a hospital; or running short, tightly defined programmes pulling together experts from a range of places to solve a particular challenge. Involving large procurers of imaging equipment such as the NHS in providing purchasing support and a buoyant home market in this technology would also be helpful.

The UK also has a leading technological position in novel security imaging devices and could capture a market value of between \$0.4 billion and \$5 billion. **A particular challenge for growing UK business in this sector is access to the facilities needed to test and develop detector prototypes. Development of either a UK or EU rapid prototyping silicon foundry is needed, with clear rules on IP sharing/protection.**

Potential government procurement contracts for innovative technology would also help to support the development of a UK-based business around this market.

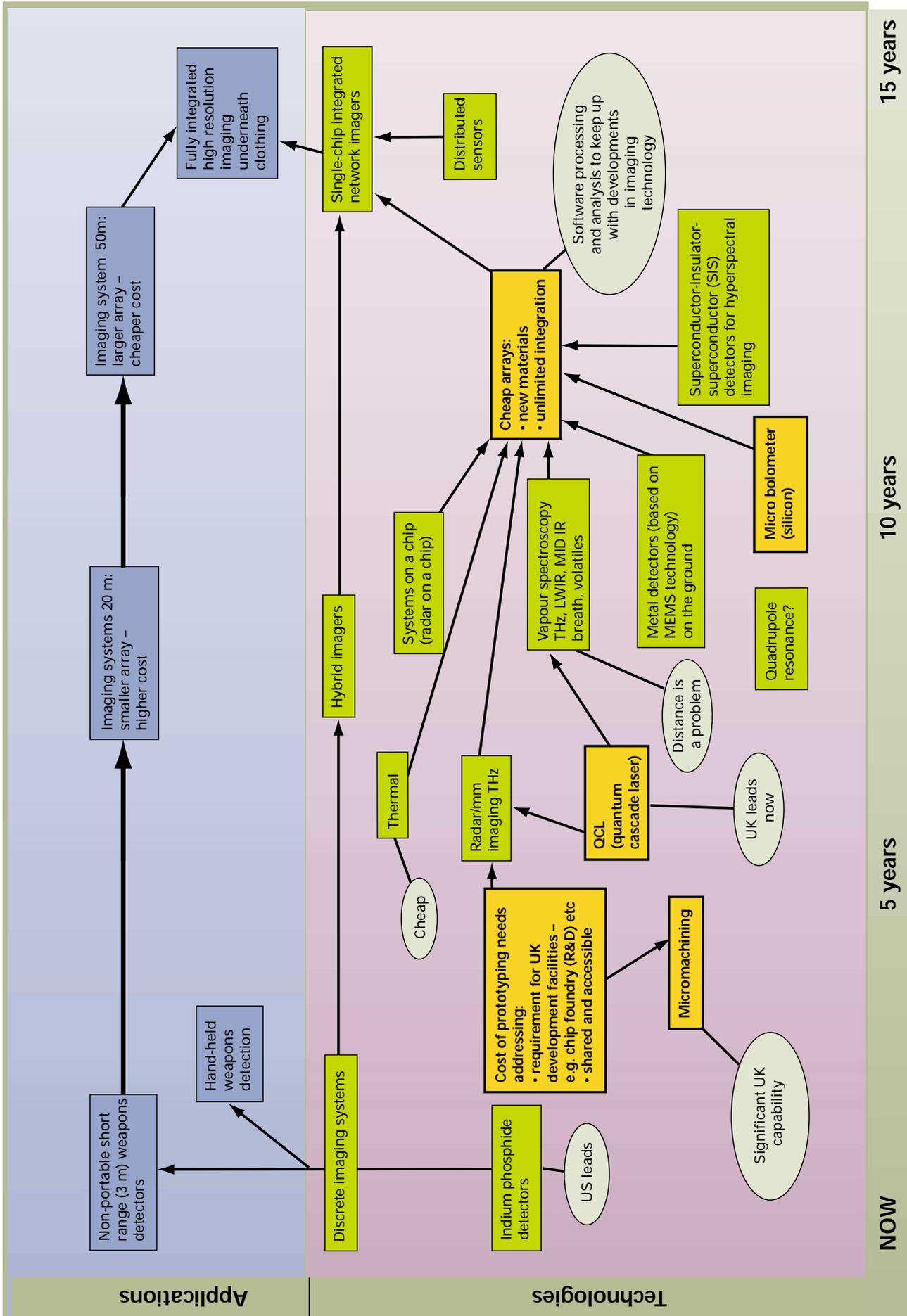


Figure 9. Non-intrusive imaging: technology timeline for security imaging (key steps shown in orange)

EPSRC, the MRC, the Department of Health and the CCLRC are exploring ways of improving multidisciplinary working on medical imaging and the prospects for a 'smart agent medical imaging centre'.

Acknowledgements

We would like to thank all members of the action group who gave so generously of their time and expertise.

Dr Brian Allen, e2v Technologies

Professor James Barlow, Imperial College London

Professor Sir Michael Brady, Oxford University

David Burrows, DSTL

Professor David Delpy, University College London

Dr Peter Dukes, MRC

Dr Matthew Hogbin, Home Office

Dr Elizabeth Hylton, EPSRC

Mrs Mel King, Department of Health

Dr Ian McDougall, Oxford Instruments

Dr Andrew Mackintosh, Oxford Instruments

Dr Brian Maddison, CCLRC Rutherford Appleton Laboratory

Professor Paul Matthews, Oxford University

Dr Delyth Morgan, MRC

Dr Douglas Paul, Cambridge University

Professor Michael Pepper, Cambridge University/TeraView Ltd

Dr Allyson Reed, QinetiQ

Dr Clifford Smith, Amersham plc

State of the science review author:
Dr Douglas Paul, Cambridge University



Printed in the UK on recycled paper with a minimum HMSO score of 75.
Department of Trade and Industry.
© Crown Copyright. www.dti.gov.uk DTI/Pub 7250/1k/04/04/. URN 04/856