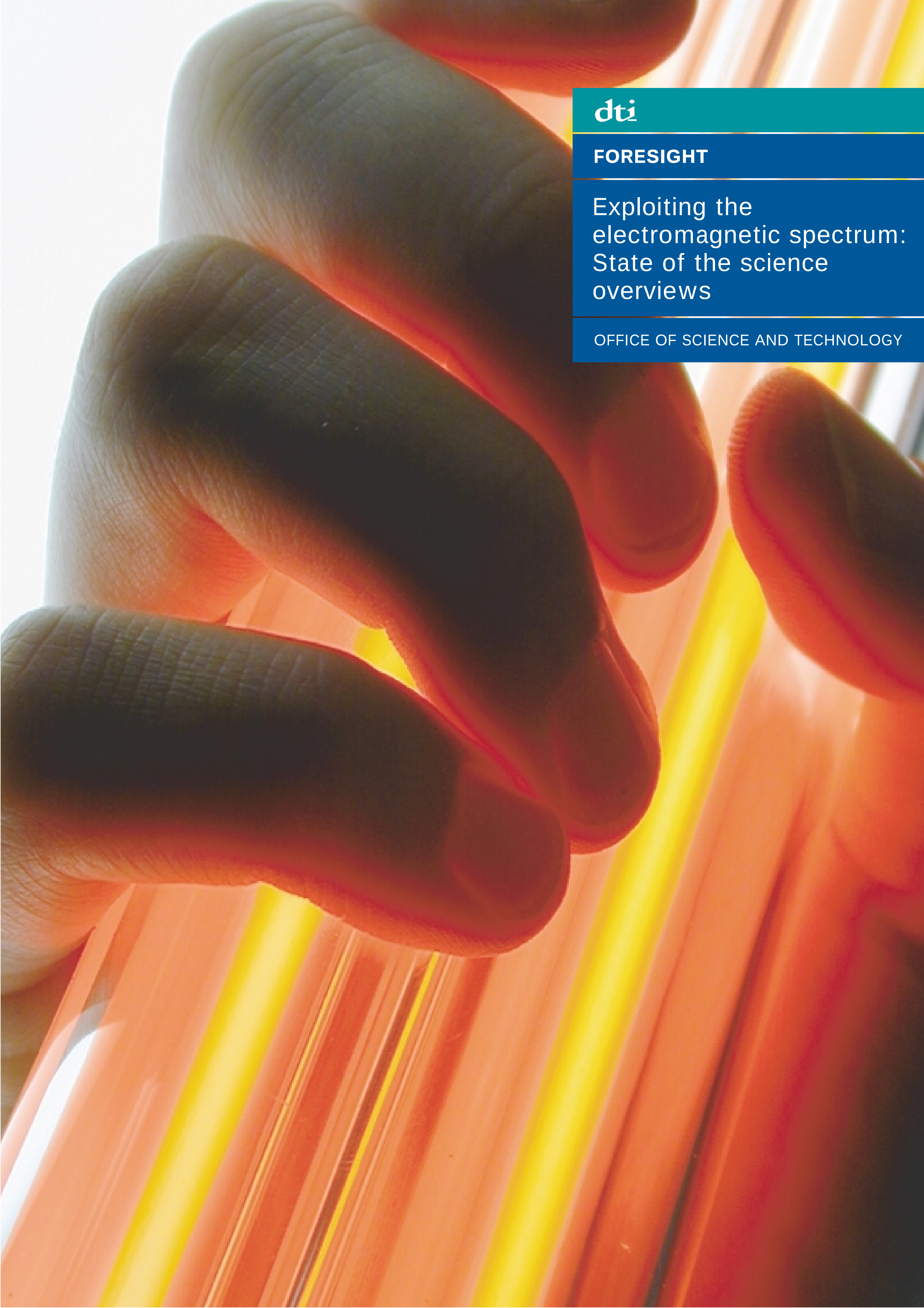


dti

FORESIGHT

Exploiting the electromagnetic spectrum: State of the science overviews

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

State of the Science Overviews

Introduction

Many technologies already make good use of some part of the electromagnetic spectrum: telecommunications networks carry signals as light waves down optical fibres; mobile phones send microwave signals through the atmosphere; and x-rays have been used for more than a century in medical imaging. Now, however, new methods of manipulating electromagnetic waves are on the brink of revolutionising many established technologies and making new ones possible.

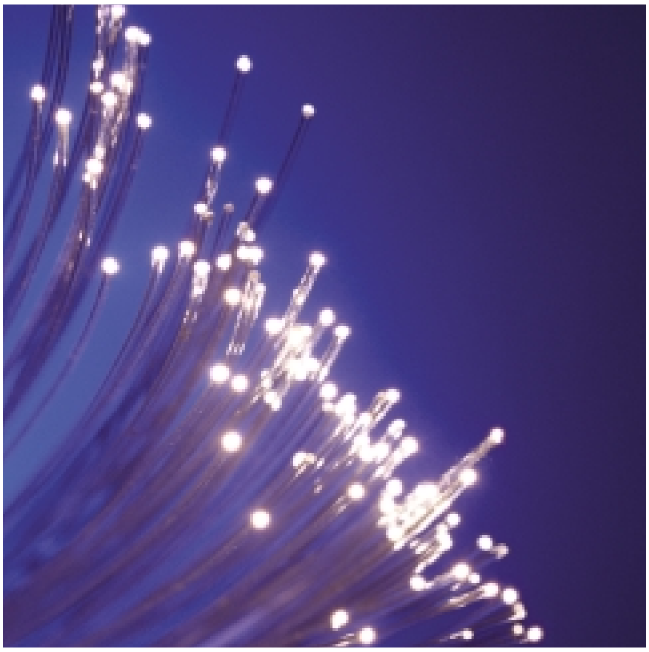
The aims of the Foresight ‘Exploiting the electromagnetic spectrum’ (EEMS) project were to identify key areas of long-term opportunity across the spectrum, assess these against UK capabilities and agree a plan of action to help the UK exploit these areas. Four topic areas were selected through a rigorous scoping process, involving the academic, business, and user communities, along with representatives from other government departments and funding bodies. As part of the detailed study of these four topics, state of the science reviews were commissioned for each.

Written by experts in the field, these reviews are technical documents that have been used to help inform the drawing up of technology timelines and plans for action. The reviews look at new technological advances, assess their likely impacts in 10–20 years’ time and consider the UK’s relative strengths in these areas. This report provides short and accessible overviews of the state of the science reviews that have been written for the project by Judy Redfern, an experienced science journalist.

Switching to light: all-optical data handling

Introduction

Bottlenecks occur in communications networks because optical signals must be converted to electrical signals for routing and processing. This review looks at the prospects of speeding up networks by developing all-optical methods of signal processing.



Over the past 20 years, optical fibre has taken over from copper cable as the medium by which data is transmitted over the telecommunications network. Only the final link to your home remains via copper cable. Instead of travelling as pulses of electrons down a wire, the data is encoded onto a light wave that travels along an optical fibre. However, some of the properties that make light so superior for carrying data make it difficult to route to ensure the data reaches the right destination. Light is good for transmission, but electricity is easier to manipulate and so is better for switching and routing.

Current networks get around this problem by converting the optical signal to an electrical one for routing, and then back to an optical signal for onward transmission. However, the conversion process introduces a bottleneck because it is slow and limits the information transfer rate. At current volumes of telecommunications traffic, such bottlenecks are not an issue, but they will become significant as we move into a broadband future.

The problem would be solved if the signal could be kept in optical form throughout the switching and routing process. To achieve this, there are major science and engineering challenges to be tackled. For example, a ‘memory’ is a key feature of any router. Electronic memory is easily available, but an optical memory is very hard to make – light signals are just too fast and slippery to be held in one place for more than a moment. Nonlinear optical techniques, made accessible by confining light in tiny spaces, offer some prospects, as do fast-tuning lasers. But the ‘Holy Grail’ of an ultra-fast all-optical network may have to wait for new approaches to reach greater maturity. The most promising appear to be photonic bandgap structures, new materials that can manipulate light in novel ways.

In the meantime, hybrid systems are under development that route and switch an optical signal electronically, without converting it. Research is also going on into network architecture since the structure of a network can have a considerable effect on the amount of routing and switching needed.

The following summarises research on routing and switching, networks, emerging technologies and finally, as a postscript, the synergy between research into optical communications and quantum computing and cryptography. First, however, we take a look at the basics of optical transmission and the state of the art in fibre development.

Optical transmission

The increase in the transmission capacity of optical fibre has more than kept up with the growth in data traffic.

An optical fibre consists of a glass core surrounded by cladding made from a slightly different type of glass. The careful choice of materials ensures that light is confined to travel along the core by a process known as total internal reflection: whenever the light beam hits the interface with the cladding it is reflected back towards the core.

Optical fibres can carry far more data than copper wires. As each fibre is no more than a hair's breadth thick, many can be bundled into one cable. Light also has another advantage: because different wavelengths do not interact with each other, data can be transmitted on closely spaced wavelengths without risk of cross-talk. This means that data can be carried on several hundred different channels down one fibre, a process called wavelength division multiplexing.

In designing the optimum optical fibre, researchers need to address three main limitations: attenuation, dispersion and nonlinear impairments. Attenuation causes the strength of the signal to drop off rapidly after travelling a few kilometres. Dispersion causes the different wavelengths of light in the signal to spread out. Nonlinear impairments result from weak interactions between wavelengths in neighbouring channels and cause signal distortion.

Minimising these limitations depends on an optimum choice among a number of factors: the wavelength of light and the wavelength range; power per wavelength; channel spacing; the composition of the optical fibre and its cladding; the diameter of the core; and how the light signal is packaged and introduced into the fibre. Attenuation, however, can never be entirely eliminated, so amplifiers are required to boost signals over more than about 80 km. The erbium-doped fibre amplifier was the first device capable of doing this entirely optically for many different wavelengths simultaneously.

The current state-of-the-art fibre, a so-called 'standard' single-mode fibre, operates over a broad spectral range from 1,260–1,625 nanometres (10^{-9} m), is impervious to water (which if allowed to penetrate a fibre will absorb signals in the 1,300–1,400-nanometre range) and has a very narrow core diameter (9 micrometres) to eliminate dispersion. The fibre's spectral range gives it a frequency bandwidth of 35 THz, which is more than enough to carry all the traffic on the US internet. At present, fibre capacity outstrips demand and hence the drive for further improvement is minimal.

Routing and switching

All-optical routers and switches require optical processing which is at the cutting edge of scientific research. Hybrid systems that process electronically tagged optical signals could offer an interim solution.

Research in optical processing has centred on developing a method based on a loop of optical fibre. Light entering the loop can leave by one of two exits depending on whether a laser beam is also flashed into the loop. The decision 'on' or 'off' is very fast, but the device is physically too big for use in most networks and there is little scope for miniaturisation because of the limit on how far optical fibre can be bent.

Hybrid devices, in which a signal remains optical throughout but has an electronic label for switching and routing, show more medium- to long-term promise. Several have been developed. One of the most promising is a switch based on microelectromechanical systems (MEMS) technology. It consists of tiny mirrors etched onto silicon in much the same way that transistors are etched onto an integrated circuit. The mirrors move in response to an electrical signal and can be directed to send an incoming wavelength to a specific output port. MEMS switches with thousands of tiny mirrors, offering more than 10 terabits per second of switching capacity, have been demonstrated, but their practical use is limited because they allow the signal to degrade. However, simple MEMS switches, with no more than 16 x 16 input x output channels, are under test in networks in Japan.

The problem of degradation is a serious one for all-optical networks. It is avoided in today's networks because the optical signal goes through regular electrical conversion, a process that regenerates a perfect copy of the original optical signal. An all-optical method of regenerating hundreds of wavelengths simultaneously is one of the most pressing needs for any system in which the optical signal is not regularly converted.

Networks

Bottlenecks can be circumvented by redesigning networks to minimise the need for processing at network nodes.

At present, when a message, say e-mail, enters a telecommunications network, it typically consists of several packets, each of which is labelled with the recipient's address. Packets are routed through the network individually via nodes that decide on the next leg of the route, given the density of network traffic. When the packets are near their destination, they are re-assembled into the original message for delivery. Packets travel between nodes as optical signals, but they have to be converted to electronic signals for processing at nodes.

Just as it can be quicker to take a long route via backstreets to avoid a hold-up at traffic lights, so conventional packet-switched data networks route packets to avoid bottlenecks at nodes. However, they under-use the bandwidth available in the optical cable between nodes. Network architectures are under development that could reduce the need for processing at nodes in order to concentrate on making the best use of this bandwidth. The simplest is a wavelength-routed optical network (WRON) in which lightpaths are kept 'alive' across the network irrespective of the amount of data being sent. In more sophisticated architectures, such as optical burst or optical packet-switching networks, messages are broken up into packets and are either aggregated into wavelength 'bursts' before being sent across the network to the exit point or are transmitted as individual wavelength packets.

These architectures work more like the old-fashioned Royal Mail than today's packet-switched data network. For example, just as the sorting office puts all parcels for Glasgow into a van bound for that city, so an entry point to an all-optical network, say an internet service provider, assigns all e-mail messages bound for Glasgow to the same wavelength. In a WRON, each e-mail will go immediately whether the wavelength is full or not, equivalent to sometimes sending a van with only one letter in it. WRONs will be efficient only when traffic volumes are so high that, in practice, wavelengths are always nearly full. In an optical burst network, the wavelength, just like the Glasgow-bound van, will set off at certain times or when enough messages or parcels have accumulated. When it reaches its destination (the Glasgow sorting office or exit point) the parcel or e-mail is delivered to the right destination via a local service or network. The more sophisticated the architecture, the more efficient the use of the network capacity, but the greater the demands on data storage and processing in routers at the network edges.

Photonic bandgap structures

Photonic bandgap structures offer the best prospects for creating all-optical routers and switches.

Fully satisfactory all-optical routers and switches need optical memory and processing that exceeds the performance of their electronic equivalents. Recently developed photonic bandgap structures offer the best prospects for creating dense and potentially nonlinear integrated optical circuits on which can be grown tiny components and waveguides.

A photonic bandgap structure consists of a material (such as glass) into which a periodic pattern of holes has been etched. The pattern of holes determines the path of the light (typically, it travels through the glass avoiding the holes) and can be designed to deflect light round sharp bends. Tiny waveguides, unconstrained by the bending-limit disadvantage of optical fibre, can be created.

Photonic bandgap devices could even be made from fibre. Photonic crystal fibre consists of glass fibre penetrated longitudinally by a number of hollow tubes. The positioning and size of the tubes affects the fibre's properties, opening up the possibility of designing optical switches within a fibre itself.

Quantum technologies

Many of the principles underlying the design of an optical network will also apply to the design of a quantum computer and there will be synergy between research in the two areas. Developments in quantum cryptography, however, will have a more immediate impact. Quantum cryptography detects the presence of an eavesdropper on the line from the disturbance caused to the quantum state of a single photon. It is only effective over optical channels and has so far been tested over distances of 40–60 km.

Further details

This topic overview draws on the state of the science review for the ‘Switching to light: all-optical data handling’ topic written by Polina Bayvel, Michael Dueser and John E. Midwinter for the Foresight ‘Exploiting the electromagnetic spectrum’ project. This document, the other three state of the science reviews and details of this project, are available on the CD-ROM that accompanies the Foresight EEMS launch pack and on our website at:
http://www.foresight.gov.uk/emspec.html

Manufacturing with light: photonics at the molecular level

Introduction

New techniques are becoming available that expand the ways that light can be used to manipulate and examine objects at the molecular scale. This review looks at these and related applications, including biomolecular manipulation, personalised drug production and micro/nano-scale fabrication.

The four key technologies identified within this review are:

Optical tweezers: Shine a focused laser beam on a microscopic particle and you can hold it in position, or move it alongside another particle to see how the two interact. Laser beams that perform such feats are known as optical tweezers. Of enormous use in research, optical tweezers could find more widespread use in routine chemical testing.

Probing and controlling chemical reactions: Light's ability to initiate and then provide information on chemical and biological reactions is also already widely used, but in the lab rather than in industry. However, this topic raises the tantalising possibility that light could be harnessed to produce tailor-made drugs and chemicals on an industrial scale.

Laser micromachining: Lasers are already used as industrial tools to machine bulk materials, such as steel. Laser micromachining is being developed to perform much smaller-scale tasks such as sculpting the tiny cogs and wheels of micromachines. Lasers provide a remarkably gentle and precise way of sculpting almost any material.

Photonic crystals: Photonic crystals can squeeze light into tiny (sub-wavelength) spaces, reducing it to a size suitable for probing or moving molecules. Photonic crystals are artificially created materials that manipulate light in much the same way as a semiconductor manipulates electrons, enabling photons to be redirected and stored. Just as developments in semiconductor technology forged the electronics revolution, so developments in photonic crystals could pave the way for all-optical telecommunications networks and optical computing. Photonic crystal fibres (optical fibres that incorporate photonic crystals) are already commercially available, but there is enormous economic potential in the development of a wide range of photonic crystal devices. Of all the technologies investigated in this study, photonic crystals show perhaps the greatest promise for future exploitation.

These four technologies are underpinned by laser technology, which has undergone rapid development over the past 5–10 years. Cheap, small, high-power lasers are now available that can focus beams to a spot less than a wavelength in diameter. The shortest possible laser pulse has also decreased to just a few femtoseconds (10^{-15} s), with attosecond (10^{-18} s) pulses on the horizon. Light travels just 0.0003 millimetres in one femtosecond and 0.3 nanometres (10^{-9} m) in one attosecond. Such short laser pulses can manipulate matter on these molecular scales. It is this shrinking of both size and pulse, together with finer control over the beam, that has opened up new uses for lasers. These advances are being matched by the development of new materials capable of exploiting such finely tuned light.

Optical tweezers

Lasers are already used like tweezers to hold and manipulate microscopic particles. The challenge for the future is to manipulate more than one particle simultaneously.

Like a moth attracted by a candle, a microscopic particle is trapped where the light intensity is highest, in the middle of a highly focused laser beam. The particle can be moved around in three dimensions and even rotated rapidly by moving the beam or by giving it an intrinsic ‘twist’. Conversely, by monitoring the particle’s position, it is possible to sense the forces acting on it, for example, when it is brought close to another particle.

One way of trapping several particles at once is to time-share the laser beam between them. An alternative is to use an array of focused beams produced by a hologram to make multiple 'optical traps' to hold many particles in place. The best and most adaptable way of creating such holograms is with spatial light modulators, which consist of a matrix of liquid-crystal cells that can be manipulated individually to create the desired hologram. Spatial light modulators can be reprogrammed rapidly to change the hologram, making them ideal for the real-time, three-dimensional manipulation of an array of optical traps.

As well as measuring forces between particles, arrays of traps can also be used to sort particles according to size, for example, to separate chopped-up pieces of DNA for genetic sequencing. However, optical traps are too large to pin down most DNA fragments, which are smaller than the wavelength of light. New techniques under investigation for trapping nanometre-sized particles include attaching micrometre-sized ‘handles’ to them to make them larger, and making smaller traps by exploiting new methods of squeezing light to sub-wavelength sizes. These methods include using photonic crystals and exploiting near field effects, which occur when light interacts with a surface (see the ‘Inside the wavelength: electromagnetics in the near field’ review).

Alone, optical tweezers and traps are research tools of enormous potential, mainly because of their ability to handle micro- and even nano-sized particles. Integrated onto a chip with other techniques, such as microscopy and spectroscopy, their use could extend to routine analysis of biological and chemical samples, for example, in the doctor's surgery, for environmental monitoring or even for forensic testing.

Probing and controlling chemical reactions

Using lasers pulsed for fractions of a second it is already possible to watch chemical reactions taking place. The future holds possibilities of using laser pulses to watch the movement of electrons within atoms.

Typically, chemical reactions at the molecular level occur on femtosecond timescales. Shine a femtosecond pulse of laser light of the right wavelength at a molecule and you can initiate the reaction. Shine further pulses a few femtoseconds later and you can 'watch' the reaction as it occurs, rather than having to infer what happened from the end products. Like taking a series of snapshots to make a movie, femtosecond laser pulses record chemical reactions, as they take place.

Many spectroscopic techniques are available or under development for working out the nature of the chemical reaction from how it changes the incident light. Conversely, it is possible to influence the outcome of a chemical reaction by choosing an appropriate laser pulse shape. The pulse shape can be modified until the desired reaction is achieved.

Although much remains to be done with femtosecond laser pulses, work is underway with even shorter pulses that could probe processes that occur on attosecond timescales, such as the movement of electrons within atoms. Attosecond pulses can only be produced indirectly by shining a femtosecond pulse into a gas of atoms such as deuterium. The femtosecond pulse excites electrons in the gas, leading to the emission of attosecond pulses of x-rays and extreme ultraviolet light. The short wavelength, as well as pulse length, of attosecond sources will open up new applications, in particular in studying biological processes.

Finally, femtosecond laser pulses shining on a nonlinear crystal can generate terahertz radiation, which lies between the microwave and infrared bands of the electromagnetic spectrum and is otherwise difficult to generate. Terahertz radiation could be used for safe medical or security imaging because, unlike x-rays, it can penetrate materials without damaging them.

Laser micromachining

Pulsed lasers can also be used for micromachining and for three-dimensional imaging.

The shorter the laser pulse, the less the thermal damage around the machining site. The heating is so fast and extreme that only a localised surface layer of material is vaporised, leaving underlying layers unheated and undamaged.

The ability of lasers to machine almost any material makes the technique particularly attractive to industry. Nanosecond (10^{-9} s) pulses are short enough for most applications. Research to increase laser power, repetition rate and develop optics for highly focused beams will result in greater uptake by industry over the next few years. However, shorter femtosecond pulses could be useful for niche applications such as the machining of microscopic devices (for example, microelectromechanical systems – MEMS) out of silicon-based materials.

Femtosecond laser pulses are also finding uses in biomedicine, for example, to build up a three-dimensional image of brain-tissue samples. The first pulse images the tissue surface and the next ablates it to expose a fresh surface for imaging – and so the process repeats until the image is built up. Femtosecond lasers might also find new uses in medicine, for example, in eye and ear surgery, dentistry, and in angioplasty where they could be used to ablate plaque from blocked artery walls.

Photonic crystals

New materials are under development that can manipulate and control light. The most promising are photonic crystals. They will have a major impact on many of the areas considered by this Foresight project.

Photonic crystals can manipulate light to perform many functions that would otherwise be difficult, if not impossible. For example, they can be designed to reduce the diameter of a laser beam to much less than a wavelength, opening up the possibility of trapping molecules which are too small to be trapped by an ordinary laser. They can also be designed to transmit just one wavelength, to spread a narrow band of wavelengths into a broad band of intense white light, to change the direction of incident light, or even to slow it down. These and other abilities are opening up an enormous number of new applications, including the 'Holy Grail' of optical processing and computing.

Photonic crystals consist of a material into which a three-dimensional periodic pattern of holes has been etched. By careful choice of the material, the size and spatial arrangement of the holes, and the placing of defects that interrupt the periodicity of the hole arrangement, photonic crystal structures can be created that perform for light all the functions that semiconductor integrated circuits perform for electrons. A lot of research is underway worldwide into the design of photonic crystal circuits and integrated chips, the types of material they could be made from, and efficient methods of manufacture.

Materials under investigation include organic semiconductors, liquid crystals and even assemblies of colloids (suspensions of small solid particles in a liquid) made with the aid of optical tweezers. Manufacturing methods include new methods of lithography such as embossing, microcontact printing and micromoulding.

Photonic crystals can also be made into fibres. Many different fibre designs already exist, the two most promising for near-term application being single-mode and hollow-core fibres. In a single-mode fibre, light travels though the transparent material, avoiding the holes. In a hollow-core fibre, light travels through a central hole, which is typically filled with air, allowing very high powers to be carried without the fibre disintegrating.

Various effects, known as strong nonlinear optical effects, make single-mode fibres particularly promising for use in telecommunications, but more research needs to be done on reducing losses before they can compete with traditional optical fibres. The nonlinear effects can also turn a narrow bandwidth laser beam into a broad bandwidth, but intensely bright, white light source with many potential uses, for example, in coherence tomography, a medical imaging technique. Hollow-core fibres could be useful gas sensors, as the laser will determine the composition of the gas in the hole.

Research into photonic crystal fibres is feeding into the other three key technologies identified in this study by aiding the development of lasers themselves. The fibres are at the cutting edge of research to improve laser beam delivery systems.

Further details

This topic overview draws on the state of the science review for the 'Manufacturing with light: all-optical data handling' topic written by Kishan Dholakia and David McGloin for the Foresight 'Exploiting the electromagnetic spectrum' project. This document, the other three state of the science reviews and details of this project, are available on the CD-ROM that accompanies the Foresight EEMS launch pack and on our website at:

http://www.foresight.gov.uk/emspec.html

Inside the wavelength: electromagnetics in the near field

Introduction

Mobile communications, imaging and flat-panel displays could be revolutionised by new materials that can control previously unused physical properties of light and electromagnetic radiation (the near field).

A new class of artificially created materials, known as metamaterials, is set to have a major impact on a broad range of technologies, including mobile communications, medical imaging, communications between and within computer chips and flat-panel displays. Negative index materials, one type of metamaterial, exploit the so-called near field that always exists close to a source of electromagnetic radiation, but tails off rapidly at distances longer than a wavelength. Unlike the more familiar far field, which propagates away from a source, the near field transports no energy from the source unless it is intercepted. Negative index materials, however, are able to manipulate the near field to dramatic effect: they display some novel and surprising electromagnetic properties.

An electromagnetic source can be thought of as a place where radiation emerges from one medium into another. Familiar sources include a glass lens, a light bulb, a radio mast for broadcasting TV signals and a waveguide horn which emits microwaves. For visible light, wavelengths are very short ($4–7x10^{-7}$ m) so the near field decays too close to the interface to be intercepted casually. But microwaves and radiowaves have wavelengths ranging from a few centimetres to hundreds of metres. When you use a mobile phone, for example, your head is in the near field of the microwaves emitted by the phone's antenna, which have wavelengths of tens of centimetres.

At optical wavelengths, near fields have little impact and so have been largely ignored. At longer wavelengths, their impact needs to be managed. Antennas and radio transmitters, for example, should be designed to divert or minimise them, so that they do not drain energy unnecessarily from the power source, such as a battery, or from the propagating far field. With a few notable exceptions, the near field has often therefore been seen as a mild irritant that is difficult to manage. With the development of the new negative index materials, however, that attitude is changing.

Capturing near fields

Materials are being developed to control the near field for new applications.

The scanning near field optical microscope (SNOM) is one of the notable exceptions where near fields have already been harnessed and put to good use. It works by placing a sample within a wavelength of visible light of the tip of a sharpened optical fibre so that the sample's surface is within the near field created at the optical fibre tip. The sample picks up energy from the near field that affects the light that would otherwise be reflected at its surface. Detail about the molecular structure of the surface can then be revealed.

A negative index material, however, placed in a near field would capture almost all of it and reduce the reflected beam to near zero. What is more, it would capture the near field from a distance much further than a wavelength away from a source. Negative index materials have some very unusual properties. For example, an electromagnetic wave travelling through such a material appears to transmit energy one way while travelling in the opposite direction; and rather than decaying within a wavelength, a near field entering a negative index material would actually be amplified. Their most remarkable property, however, is that they have a negative refractive index.

Refractive index gives a measure of the extent to which a material deflects the path of a light beam entering it. The deflection comes about because light travels through different materials at different speeds. When it travels through air into glass, for example, it slows down and thus changes direction at the interface between the two media. All natural materials have a positive refractive index because they bend light away from the surface. Negative index materials, however, bend it in the opposite (negative) direction – hence their name.

Victor Veselago, a Russian physicist, first explored the idea of negative index materials in the 1960s. But it was not until 1999 that John Pendry from Imperial College, London, and colleagues at Marconi UK first described how they might be made. They realised that structures consisting of a periodic arrangement of certain electronic components could look, from a microwave's point of view, like a material with a negative index. In 2000, David Smith from the University of California, San Diego, produced the first true negative refractive index material. It consisted of arrays of fine wires sandwiched between sheets of fibreglass onto which had been printed copper, millimetre-sized, electronic components called split-ring resonators.

Research is now centred on developing different types of negative index material with electromagnetic properties to suit different uses and wavelengths. These materials could be used to control, route and amplify the near field. This ability to tailor a material for a use is leading to new science and applications.

Applications: antennas, magnetic resonance imaging and flat-panel displays

The new materials could reduce energy usage by mobile telephones, produce lightweight radars, reduce the cost and size of magnetic resonance imaging, be used in ‘real’ (viewable from all angles) flat-panel displays and in the next generation of data-storage devices.

Research on negative index materials has also given a boost to the search for innovative ways of using more conventional materials to capture near fields. For example, some UK companies are developing antennas with ceramic cores that trap the (in this case unwanted) near field. However, such conventional materials can be heavy, expensive and difficult to make, so antenna designers are turning to the new materials and coming up with some interesting ideas. One application, under development by Boeing in the US, is to use lenses made of negative index materials for radar. A lightweight concave lens made from a negative index material could do the same job as a much heavier, more expensive and more difficult to manufacture convex lens made from a conventional material.

In magnetic resonance imaging (MRI), negative index materials could fulfil a role that conventional materials cannot because they can operate in a high magnetic field without disturbing it. In MRI, a sample, usually a patient, is placed inside a powerful magnetic field. The hydrogen atoms in the patient's body line up in the direction of the magnetic field. A radio frequency pulse disturbs this alignment and the picture is formed by collecting the characteristic radio waves emitted by the atoms as they realign with the magnetic field.

A major drawback with MRI is that the resolution of the image is limited by the wavelength of the radio waves emitted by the atoms. The only way of reducing the wavelength at present is to increase the magnetic field strength which is difficult and expensive to do. A solution for the longer term, however, could be to capture the sub-wavelength details in the near field using a 'superlens' made from a slab of negative index material.

One interesting application for surface media, under development in Japan with supporting research in Europe, is in flat-panel displays. The light in such a display would emerge as tight beams from holes in the surface media material. Different colours could be selected by adjusting the viewing angle. The most important future applications of surface media, however, are likely to make use of their ability to focus light to a spot smaller than its wavelength. For example, the amount of information that can be written onto a CD or DVD is limited by the diameter of a laser beam, which is limited by the wavelength of laser light. At present, one feature film can be comfortably recorded onto one DVD. Being able to focus a laser to a spot much smaller than its wavelength could lead to DVDs with up to 1,000 movies recorded on each.

Further details

This topic overview draws on the state of the science review for the 'Inside the wavelength: electromagnetics in the near field' topic written by Anthony Holden for the Foresight 'Exploiting the electromagnetic spectrum' project. This document, the other three state of the science reviews and details of this project, 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**

Picturing people: non-intrusive imaging

Imaging technology is already widely used for applications such as CCTV and medical imaging. New science promises significant advances in these areas.

Go to an airport and you will have to walk through a metal detector before boarding the plane. Walk around any city centre and the chances are that your image will be recorded on numerous CCTV cameras. Go to hospital and you may well have an ultrasound scan or be subjected to some other imaging technique. Non-intrusive imaging, whether for security or medical purposes, is widespread and almost everybody nowadays will encounter it at some stage in their lives. New imaging techniques are becoming available that will increase the capabilities and pervasiveness of non-intrusive imaging in the near-to medium-term future.

Most of the electromagnetic spectrum, from very long radio waves to high energy x-rays, is used in some way for imaging. Until very recently the notable exception was terahertz waves, which are shorter than microwaves but longer than visible light. The problem has been the lack of cheap sources. That is now changing, however, with the availability of the first commercial terahertz imaging system through a UK company.

Terahertz security imaging

Terahertz and millimetre waves may herald a new generation of CCTV-type technology to check for weapons, explosives and drugs.

As terahertz radiation reacts with all molecules, many applications are opening up, ranging from the detection of skin cancer to the detection of landmines. Most significant, however, is likely to be the identification of people who are a security threat, especially suicide bombers who need to be stopped tens of metres before they reach a target. At present, the only acceptable way to find a hidden weapon is to search the suspect by hand. The routine use of x-rays, which can reveal metal objects such as guns, is unacceptable because of the health risks from low doses of ionising radiation. Furthermore, x-rays cannot pick out non-metal objects, such as ceramic knives or plastic explosives. Terahertz radiation, however, can penetrate clothing from a distance to reveal and identify many types of hidden material including narcotics as well as explosives and other weapons.

Microwave radiation is also under development for security imaging. Originally developed to see through fog and rain, microwave imaging has also been used to detect weapons hidden under clothing and illegal passengers hidden on lorries that have non-metallic sides. Lower-frequency microwaves penetrate clothing and the atmosphere better than higher frequencies, but as the wavelength is longer, the resolution is poorer.

Hybrid systems

Improved medical imaging will allow diseases to be spotted and diagnosed at much earlier stages, without biopsy and with less use of damaging ionising radiation.

In medical imaging, research is directed at improving the resolution of existing techniques and at developing new technologies to replace those that use ionising radiation, particularly gamma cameras and positron emission tomography (PET) and to a lesser extent x-rays. Improved resolution will allow individual cells and molecules to be imaged so that disease processes can be detected before they lead to gross anatomical changes. At present, however, techniques using ionising radiation, such as PET, are often the only way of providing information on metabolic or physiological processes and they are unlikely to be superseded in the near future.

Hybrid imaging systems that combine two techniques and, in the process, optimise both, are showing promise of improving resolution and reducing exposure to ionising radiation. For example, MRI provides good structural information but, even with the best existing machines, the resolution is limited to about 1 millimetre. PET can detect the high metabolic activity of, say, cancer cells by measuring gamma rays given off by a radioisotope introduced into surrounding tissue, but the resolution is poor. By combining the two techniques, however, the position of cancer cells can be located within an anatomical structure and the boundaries of the tumour located with greater precision than with either technique alone. Such precision could be used to guide surgery and also to monitor treatment progress.

Improved magnetic resonance imaging

Smaller, cheaper magnetic resonance imaging will become available for health imaging, although ultrasound and infrared imaging (thermography) may capture this market.

Magnetic resonance imaging (MRI) is one of the few medical imaging techniques able to image almost any organ in the body, but, because of the high cost, it is not available in most UK hospitals. PET is also expensive and even less widely available. Research aimed at improving the performance of both techniques is unlikely to lead to cost reductions in the near future. For MRI, increasing the strength of the machine's magnetic field will improve resolution, but will involve using larger magnets or leading-edge magnet technology, which will add to costs. Machines operating at the present limits of resolution, however, are already good enough for studies that correlate individual variations in small anatomical structures with genetic variation, for example prefrontal neurons with the genetics of schizophrenia. MRI is also being developed to image metabolic processes in near real time, thus partly replacing PET. This functional use of MRI, however, also requires higher magnetic fields.

Small-scale MRI and PET scanners are under development for use in genetics studies with small laboratory animals. The miniaturisation of the technology could be applied to smaller, cheaper machines for human use. However, ultrasound and infrared imaging (thermography) show greater promise of providing comprehensive imaging systems at reasonable cost that do not rely on ionising radiation.

Lower-cost technologies with potential: ultrasound, infrared and visible imaging

The use of ultrasound as a treatment tool will increase. New medical imaging technologies based on infrared (thermography) and visible light (optical coherence tomography) are also likely to increase.

Ultrasound relies on sound waves rather than electromagnetic radiation. It has been used widely for medical imaging for many years and improvements in resolution are continuing. However, its use is now expanding to include more invasive procedures and the provision of functional information. For example, transverse-only sound waves are being developed that can be sent down a waveguide to specific locations in the body where they can perform procedures such as the safe breaking up of blockages in arteries. Ultrasound is also being developed to provide functional information, for example, changes in blood flow using the Doppler effect, which could be used to monitor the effectiveness of cancer therapies that attack blood vessel formation in tumours.

Thermography is a passive imaging technique because it relies on the detection of heat in the form of infrared radiation given off naturally by a body. Most other imaging techniques are active because they irradiate a body with some form of radiation and measure the response. Infrared technology was originally developed for night imaging for military use, but recent advances, especially in detector technology, are leading to new applications. For example, thermography is under development for routine breast cancer screening as a safer alternative to x-rays.

Visible imaging also has untapped potential for providing relatively low-cost medical imaging in a variety of settings. The disadvantage, that visible light penetrates no more than a few millimetres below the skin surface, is offset by the availability of fibre optic instruments that can deliver light to many locations within the body. Also, optical imaging systems can provide much higher resolution than MRI or other imaging techniques. For example, optical coherence tomography (OCT), a technique that provides real-time, three-dimensional images of small surface structures, is sensitive enough to guide surgery, or to measure the response of tissues to drugs. The resolution is high enough to image individual cells and research is underway to identify contrast agents that could be used to 'tag' a cell or molecule, enabling its progress to be watched as it undergoes a physiological process.

Photonic crystal optical fibres, which generate very intense broadband light sources (see the ‘Switching to light: all-optical data handling’ review), are finding some of their first applications in OCT. The range of different wavelengths delivered by a photonic crystal fibre allows different tissues to be identified in a sample through spectroscopy. This is potentially a very powerful technique that could surpass PET in the provision of high-resolution, functional imaging of structures accessible to a fibre optic instrument.

X-rays

Technology will develop to reduce doses of x-rays required for imaging; combining x-ray analysis with other forms of imaging is likely to be the key way forward.

X-ray imaging is one of the oldest medical imaging technologies and still the most widely used. It is also extensively used in security imaging of baggage and goods. X-ray images are no longer developed on film but are produced digitally. X-rays are also used to produce high-resolution, three-dimensional images using a system called computed tomography (CT). Future developments include developing better x-ray detectors, which will allow a reduction in the x-ray dose to a patient, and speeding up CT so that dynamic processes can be imaged. X-ray CT is also being fused with other techniques such as PET and MRI so that high-resolution anatomical information can be combined with functional imaging.

Use of markers to improve imaging

Advances in markers which provide the 'contrast' that allows certain imaging technologies to 'see' will lead to improved medical imaging.

One of the most significant drivers for improvements in medical imaging could be the development of new contrast agents, substances or techniques that exaggerate the distinction between different tissues and thereby improve imaging sensitivity. Contrast agents include the use of ultrasound to create tiny bubbles in a liquid, a process known as cavitation, to distinguish it from surrounding material. Advances in genetics and the study of proteins are also expected to lead to the development of new contrast agents in the form of markers or tags for specific genes or proteins that can be picked out during imaging.

The need for better software analysis

Improved resolution and new imaging techniques will produce more data that needs to be analysed and stored. The development of new software to enhance images, extract extra information or identify specific structures through pattern recognition is thus essential to interpret these data, and realise the full potential of new technologies.

Further details

This topic overview draws on the state of the science review for the 'Picturing people: non-intrusive imaging' topic written by Douglas Paul for the Foresight 'Exploiting the electromagnetic spectrum' project. This document, the other three state of the science reviews and details of this project, 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

Printed in the UK on recycled paper with a minimum HMSO score of 75.
Department of Trade and Industry.
 www.dti.gov.uk DTI/Pub 7248/1k/04/04/. URN 04/856