



Technology Sector Report

Technology Analysis of Nanophotonics

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1. Definition

Nanophotonics describes the study of the behaviour of light at sub-wavelength scales. It encompasses a wide range of materials and technologies which have applications in a number of sectors. For example, plasmonics is a promising technology which may be used to enable interconnection of optical and electronic components. However, it also has applications in fields like photovoltaics and sensing.

Professor Clivia M. Sotomayor Torres of University College Cork describes nanophotonics as:

“... the science and engineering of light-matter interactions which take place, on the one hand, within the light wavelength and sub-wavelength scales and, on the other hand, are determined by the physical, chemical and structural nature of artificially or natural nanostructured matter, it is envisaged that nanophotonics has the potential to provide ultra-small optoelectronic components, high speed and greater bandwidth.”

This report will focus mainly on the implications of nanophotonics for electronic applications. This encompasses the creation of optical components which either exist in sub 100nm length scales, or which have other key measurements (such as surface smoothness) that are in the nanometre range. Nanoscale structures, such as photonic crystals, will also be considered in view of their relevance to optical networks.

The burgeoning research area of metamaterials is also within the domain of nanophotonics. This is a field which has generated a great deal of public interest, largely because of their implications for the construction of ‘cloaking devices’.

New tools which are enabled by nanophotonics, such as near-field optics, will also be considered in this report, not least because of their applicability to lithography. Finally, plasmonics, a field which is dependent on the ability to purposefully engineer specific nanoscale surfaces.

Please note that quantum dots themselves are covered in the relevant section of the ObservatoryNano report on Materials.

2. Short description

2.1. Waveguides and Photonic Crystals

Waveguides are typically structures in which a material with a high index of refraction is surrounded by a low index cladding material. The structure is therefore able to guide photons along its length.

The wider intention behind work in this area is to integrate optical and electronic components. At present, there is a fundamental tension between optical components, which offer very high data transfer speeds but which are limited in the extent to which they can be scaled down, and electronics components, many of which exist at sub 100nm length scales. One practical reason for the scaling limits of optical waveguides is that bending light typically requires high-radius turns.

With nanotechnology smaller waveguides can be created using photonic crystals. Photonic crystals are three dimensional periodic structures, which can be made to demonstrate total internal refraction, making them suitable for sharp waveguide bends. Photonic crystals admit or reflect specific photons depending on their wavelength and the design of the crystal.

Paul Braun of the University of Illinois at Urbana-Champaign developed photonic crystal waveguides in 2002, using a polymer etching technique to create specific pathways through the crystals.

However, it has not been possible to create a three dimensional photonic crystal that reflects visible light. Michael Bartl at the University of Utah has attempted to solve this by analysing the structure of the scales of a Brazilian beetle, which exhibits these desired optical properties.

A number of groups (e.g. Technical University of Denmark, IMEC) are using electron beam lithography and deep UV lithography and to fabricate nanophotonics structures from silicon. Nanoimprint lithography has also demonstrated some utility in this area.

IBM is also prioritising silicon-based nanophotonics, due in part to the compatibility of the material with existing manufacturing processes. The company has developed silicon waveguides, which, whilst being over 200nm, require nanometre scale tolerances on the waveguide surface.

Modulators are used to convert optical signals or light waves to electronic pulses. External Light Modulators adjust the parameters of a light beam. In December 2007, IBM also released details of a silicon Mach-Zehnder electro-optic modulator. This device was orders of magnitude smaller than previously demonstrated modulators.

2.2. Plasmonics

Plasmonics *manipulates light with metals*. Metals absorb light in contrast to general materials used in optics, such as fibers and plastics. Despite absorption and thus loss of light, use of metals can give benefits you would not get with other materials. The absorption property might also in some cases be useful.

Plasmons are 'optically induced oscillations of free electrons on the surface of a metal'. They are essentially 'density waves of electrons', generated when light strikes a metallic nanostructures. The existence and behaviour of plasmons can be controlled by nanoscale engineering of the metal surfaces involved.

2.2.1. Fundamental research

Fundamental plasmonics research is trying to answer two key questions. The first question is related to *how small you can shrink light*. Based on the diffraction limit it is believed that we cannot make light smaller than half its wavelength (~500nm). Researchers are with the help of plasmonics trying to figure out how to focus light in a spot that is ~1 nm. The second question is related to the *study of the electron movements* in the metal particles. The timescale (10^{-18} s) of this movements is also interesting as it opens possibilities for e.g. Attosecond lasers pulses. In addition, research is focusing on the optimal metals to use – aluminium enables plasmons to travel furthest before dissipating. There are also potential issues with the heat generated in the metal. However, this fundamental research is still far from applications.

Examples from research and ideas for applications¹

Surface plasmon polaritons

What is it? The taper shown in the figure is used to concentrate light with a wavelength of 1500 nm to a "hot spot" with a diameter smaller than 100 nm.

For what: For example to couple light into metallic nanowire waveguides or biosensors.

Example: Haemoglobin measurements measuring the iron content in blood.

How: Nanoneedles put nanodrop of blood on sensor, the iron content is measured optically, measuring how light is absorbed. If the drop is nanosize the light needs to be guided.

Surface plasmon devices

What is it? Electrical source for plasmons.

Solving problem: Plasmons are light waves need to be generated. Currently plasmons are generated by expensive lasers, light sources, which is not applicable to most future applications.

When: Research is ready. Needs to be commercialised.

Surface plasmon cavities

What is it? A way to catch the light and keep it there.

Solving problem: Contrary to electrons that are stored in USB sticks etc, light cannot be stored. The light is trapped in the ring.

For what? In addition to light storage in general, you could combine a Plasmon ring with a LED and make it emit light more efficiently.

¹ Professor Polman et al, Center for Nanophotonics at the FOM-Institute for Atomic and Molecular Physics, the Dutch Foundation for Fundamental Research on Matter (FOM) in Amsterdam, The Netherlands. <http://www.erbium.nl/index.htm>. Reference: Interview 30.9.2009, NTE conference, Berlin

2.3. Metamaterials

In the nanophotonics context, a metamaterial is a novel material with a negative index of refraction. They are typically inhomogeneous composites with embedded nanoparticles, in which the structural elements are much smaller than the wavelength.

A variety of different metamaterial types have been developed. Researchers at Boston University have developed a metamaterial which consists of a 200nm gold layer on a polyimide substrate. At Princeton University, researchers have tuned a material to work in the infrared spectrum. The material consists of alternating layers of indium gallium arsenide and aluminium indium arsenide.

One of the most exciting applications of metamaterials involves the use of their negative refraction properties to produce what are essentially cloaking devices. David Smith of Duke University demonstrated such a device in 2006, cloaking a metal cylinder from microwaves by surrounding it with metal wires and split rings printed onto fibreglass circuit boards.

The challenge in applying this technology to cloak objects from visible light is that a metamaterial would need to be developed which could negatively refract the whole spectrum of visible light. Two papers released in 2008 identified metamaterials that approached negative refraction of the visible light frequency band. Researchers at UC Berkeley used stacked layers of silver and magnesium fluoride, which negatively refracted near-infrared wavelengths. Coming closer to the visible spectrum, another group at UC Berkeley used nanowires grown inside porous aluminium oxide, and demonstrated negative refraction at 660 nanometres.

Another application of metamaterials could be to produce lenses which are able to provide very precise focusing control, adjusted by controlling the composition of the metamaterial. A similar approach could be used to concentrate light, having applications in solar energy.

2.4. Near-field scanning optical microscopy

Near Field Scanning Optical Microscopy(NSOM) is, as the name suggests, an optical microscopy technique which is capable of resolving images at less than the wavelength of visible light (possibly down to 50nm).

NSOM devices employ a point light source, which can be obtained by using an optical fibre with a small aperture at one end, or by using an AFM tip with a hole at the point. This light source is then placed very close to the surface which is being analysed, and is scanned over the whole sample. Information about the surface is obtained by i) analysing light which passes through the sample (transmission mode), ii) analysing light that is reflected from the surface, iii) using the probe to collect light rather than to transmit it, and iv) by using the probe tip to both light and collect information about the sample.

The parameter which is measured is typically the intensity of the light, although other information can be gathered such as the refraction index, whether there is excitation of molecules, magnetic properties, and several other factors.

2.5. Lasers

A laser emits usually spatially *coherent* light through a process called stimulated emission. Coherent light means that the source produces light waves that have the same frequencies and identical phase. Most other light sources emit *incoherent* light. Lasers are capable of emitting light with a narrow wavelength spectrum, i.e. e.g. monochromatic light. There are several different types of lasers. The most commonly known are Gas, Chemical, Solid-state, Fiber-hosted, Photonic crystal and Semiconductor lasers. Semiconductor lasers are most commonly used in Telecommunications and Photonic crystal lasers are lasers based on nano-structures.

2.5.1. Lasers for materials processing

Currently material processing laser markets are worth about 1.5 billion Euros, not including telecommunications diode laser. Lasers can be divided into three categories.

1. Microtype lasers

- Include Microsecond pulses (for e.g. medical technology), Nanosecond pulses (applied to many areas depending on wavelength) and picoseconds pulses (for e.g. frail materials)
- Competes with the existing industries in medical technology, electronics, and semiconductors: production of discs and displays: chemical etching of thin films. Industries where components are made so small that traditional material processing is not possible. Also higher quality processing is possible

2. Macrotype lasers

- Includes e.g. continuous lasers
- Competes with existing (metals) industry: welding, cutting of thick metal, and gliding. Also some army applications.
- Growth of market will occur when traditional methods are replaced.

3. Marking Lasers

- Includes nanotype lasers
- Competes with printing technology, making marking cheaper
- Can be divided either by material type or size of print

3. Additional Demand for Research

3.1. Plasmonics

Plasmonics research started in Europe and still five years ago a majority of the research was done in Europe. Since the Gordon conference arranged in the US, US research has levelled with that in Europe.

In Europe Plasmonics research is very scattered, bigger research groups can be found in Amsterdam, Graz, and Barcelona. The European PLEAS project is developing plasmonic approaches to two applications; higher efficiency LEDs, and higher sensitivity photodetectors. Companies have not yet told about their ICT related plasmonics research but it is presumed that such research is evaluated in the bigger ICT companies.

In five years from now we will have greater understanding of plasmonics and whether it can be applied. If plasmonics will, e.g., be included in the Integrated Circuits-roadmap depends on the fundamental research done now and the amount of people and funding applying it.

3.2. Lasers

From the development point of view the multidisciplinary of the research makes it an challenge: knowledge in electronics, materials technology, software, optics are at least needed.

From an industry point of view the biggest challenge is the small market size of fiber lasers. As the markets are so small there are no commercial equipment suppliers and most of the equipment has to be developed in house.

More effort is needed in productisation and commercialisation of current (photonic) technologies. Currently, the biggest industry players are Rofin, Truth and Bukham/Oklaro.

In five years from now we will see a growth in the laser markets. Microprocessing using lasers will enter the markets. Lasers will become smaller and both less expensive to buy and use. In general fiber technology will become more common as it uses less power than more conventional technology.

4. Applications and perspectives

Following is a list of the many applications of nanophotonics.

4.1. Communications technology

Data networking over long distances typically employs fibre optic networks to carry data. This data then needs to be modulated from optical to electronic signals. Nanophotonics enables devices which are capable of interacting more easily with electronic networks.

4.2. Optical computers

The vision of an all-optical computer is still decades away, but nanophotonics is enabling more data transfer to take place over optical networks. An application which could have very high impact is the use of photonic connections between multiple processor cores on an integrated circuit.

4.3. Lasers

Lasers are used in thousands of highly varied applications in all industry sectors. Lasers can also be used for production of e.g. solar cells, biosensors and displays. Depending on the need, lasers can either produce a continuous beam or a series of short pulses. Lasers can also be categorised based on the output power of the laser: ranging from 1mW for laser pointers to kilowatts for industrial cutting. Lasers are also used in projectors for handheld devices, digital cameras, mobile phones, PDAs, Laser glasses (virtual retinal display) and heads up displays for cars.

4.4. Plasmonics

Applications for Plasmonics are in many fields: medical, ICT, and Photovoltaics to name a few of the most promising. An early application of plasmons was in light concentration, enabling improved performance of spectroscopy based techniques. So far, one of the most successful potential applications being developed is in cancer treatment (ref: Naomi Havash). In their approach, a very small metal particle selectively (chemically) attaches to the cancer cell. Once the metal particle is radiated with a laser through the skin it heats up and kills the cancer cell. Medical trials are on their way for this research. Another promising field is in combining optical fibers with the electronics in computers. Plasmonics could guide the light and solve the size mismatch between electronic components (which may be sub-100nm) and optical components, restricted by the wavelength of light.

To date probably the most important application for plasmonics is related to photovoltaics, where the biggest challenge is making solar cells less expensive. Present solar cells have to be thick (~0.5 mm silicon wafer), otherwise part of the red light will go straight through. With plasmonics you can engineer the flow of light so that the thin solar cell catches the whole spectrum. This is done by spraying metal nanoparticles on the solar cell, which catch the light and redirect in the solar cell so that it is very efficiently absorbed.

Another interesting application area is the application of Plasmonics to light source development. The light generated by current LEDs is scattered and does not have the right colour. If you print metal particles on LEDs, the light comes out in the right direction with the right color.

It is noticeable, that many current applications are already based on the plasmonic phenomena. An excellent example is the home pregnancy test. The test includes metal nanoparticles on the surface of the material, which have certain colour from the scattering of light. If the urine includes the pregnancy (hCG) hormone, this attracts metal nanoparticles on the surface to stick to other nanoparticles and change color. In other words the plasmons interact with each other due to the hormone.

5. Key players and experts (selection)

Europe has a number of research centres and companies working in Nanophotonics:

- Competence Centre for the Application of Nanostructures in Optoelectronics, TU Berlin, <http://www.nanop.de/>
- Institute for Atomic and Molecular Physics (AMOLF), <http://www.amolf.nl/>
- Fraunhofer Institute for Applied Optics and Precision Engineering IOF, http://www.iof.fraunhofer.de/index_e.html
- Valencia Nanophotonics Technology Center, <http://www.ntc.upv.es/english/index.html>
- Photonic Nanostructures Group (PNG) was established at the Tyndall National Institute of the University College Cork, <http://www.tyndall.ie/research/photonic-nanostructures-group/>
- Optics of Complex Systems, European Laboratory for Non-linear Spectroscopy, <http://www.complexphotonics.org>
- Photonic Crystals Group ICMM, <http://luxrerum.icmm.csic.es/>
- Nanotechnology Research Center at Bilkent University, <http://www.nanotam.bilkent.edu.tr/>
- Optoelectronics Research Center, Tampere University of Technology, <http://www.orc.tut.fi/>
- TopGaN <http://www.topgan.fr.pl/>
A manufacturer of blue/violet GaN laser diodes

There are also a number of industry bodies and companies that are working in the area of photonics:

- European Photonics Industry Consortium, <http://www.epic-assoc.com>
- Virtual Institute for Artificial Electromagnetic Materials and Metamaterials, <http://www.metamorphose-vi.org>
- NanoPhotonics to Realise Molecular Scale Technologies (PhOREMOST), <http://www.phoremmost.org> (this FP6 Network of Excellent ran from 2004-2006)
- Merging Optics and Nanotechnologies (MONA), www.ist-mona.org
- Plasmon Enhanced Photonics (PLEAS), <http://www.eu-pleas.org>
- Nano-Photonics Materials and Technologies for Multicolor High-Power Sources (NATAL), <http://www.ist-world.org/ProjectDetails.aspx?ProjectId=58a8926d32e6428384e736c22ca0788c>

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