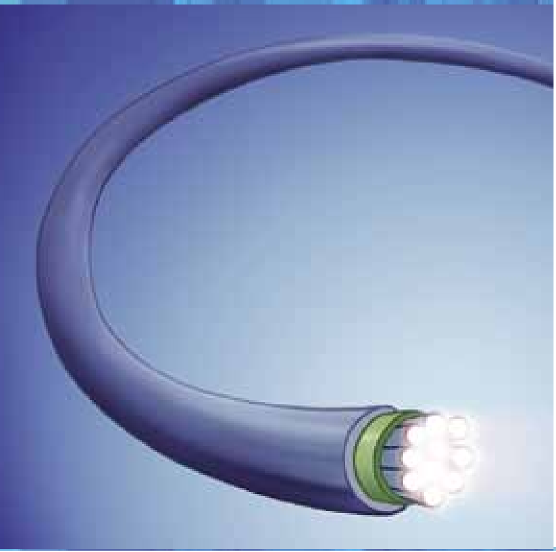


FORESIGHT:
MATERIALS FOR PHOTONICS

ACADEMY OF FINLAND RESEARCH PROGRAMMES:

Photonics and modern imaging techniques

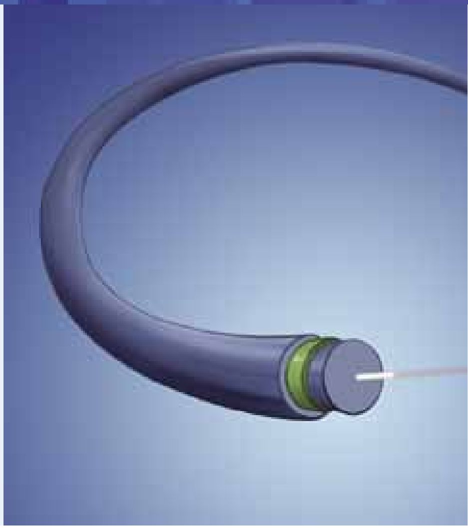
Programmable materials

ACADEMY OF FINLAND

FORESIGHT: MATERIALS FOR PHOTONICS

Introduction

Photonics materials is an important research field in Finland. While the Academy of Finland's research programme Photonics and Modern Imaging Techniques is now nearing completion, the research on Programmable Materials programme continues. Industrial interest in photonics materials is strong, and the field holds much potential for research-based new businesses and spin-offs. The objective of this foresight exercise is to provide Finnish researchers and industry with a view into some of the current trends in the field of photonics materials research with a focus on certain key areas in Finland.



Photonics plays a major role in all aspects of human endeavour. Not only does it allow addressing fundamental scientific questions but it also enables to perform key functions in fields ranging from information technology to biomedical sciences via industrial process monitoring and life entertainment. The importance of photonics as a revolutionising science has been globally recognised by policy-makers. For example, the United Nations endorses 2015 as the International Year of Light and, at the EU level, the funding for photonics has been significantly increased in the new Horizon 2020 programme.

Photonics can be regarded as one of the key enabling technologies, and it is commonly combined with micro- and nanoelectronics, biotechnology or nanotechnology. When aiming to develop new photonic components and devices, many fundamental questions on light-matter interactions need to be addressed, and providing answers to these questions will open up new avenues in various fields of science and technology. Further advances in photonics will rely on the implementation of new concepts using novel materials with tailored optical properties. Multidisciplinary research is a key factor here, requiring long-term strategic collaboration. This is particularly important in materials research for photonics, since the selection and combination of different materials and technologies is generally far from trivial.

The field of photonic materials is extremely broad, including subfields of well-established glass and semiconductor materials, polymer materials, tailored nano- and metamaterials, and emerging synthetic biophotonic materials, just to name a few. Here, a selection of future trends in materials for photonics, chosen for their importance and future commercial potential, are presented. Finland has a solid scientific and industrial background in fabrication of semiconductor materials and devices, optical fibres, low-cost polymer components by replication, and emerging tailored nanophotonic components. The current expertise in Finland in these fields is a true asset, and we can envision Finland to become highly competitive in these areas.

New photonic materials enabled by innovative fabrication technologies

The fabrication technologies play a crucial role in the development of new photonic materials and devices. Recently, new important fabrication technologies have started to emerge in photonics applications. These include roll-to-roll techniques in fabrication of low-cost polymer components, new fabrication methods of graphene and other nanocarbon materials as well as the use of atomic layer deposition (ALD) for photonics applications. In addition, the development of advanced 3D printing techniques for photonics applications has just started.

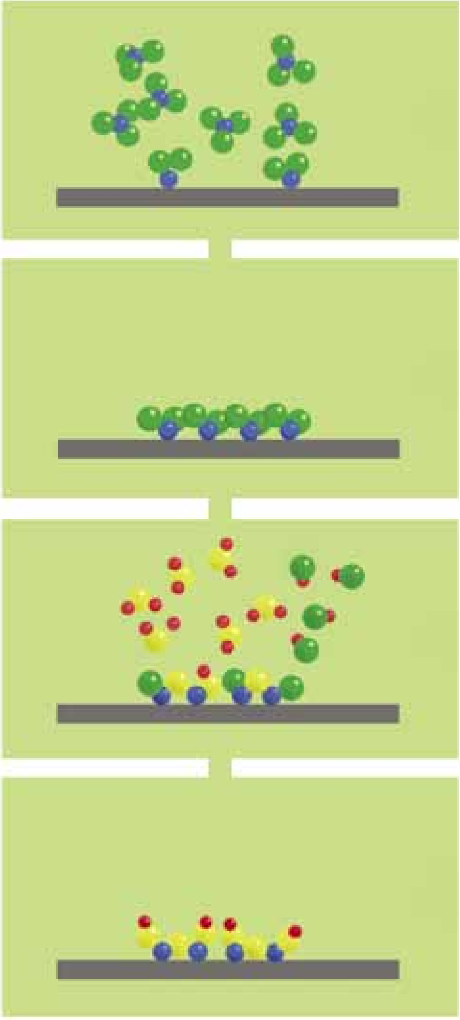


Figure 1. One cycle of an ALD-process to form Al_2O_3 *from Al precursor and water. Al atoms are shown in blue and O in yellow.*

Finland has world-leading expertise in ALD, both in academia and industry. ALD is a unique thin-film deposition method based on saturative surface reactions of alternately supplied precursor vapours. As a result of the saturation of each reaction step, the film growth is self-limiting, thereby providing several unparalleled advantages: atomic-level control of film composition and thickness, perfect step coverage and excellent large-area uniformity. These characteristics have recently started to arouse increasing interest towards the use of ALD in photonics. In planar optical waveguide devices, for example, a precise control of structure dimensions is of utmost importance, and the ability to conformally coat the nanowaveguide surface results in unique possibilities. The use of ALD can be a truly enabling deposition method for future nanophotonic devices, and the development of ALD processes for novel materials has a strong potential for significant breakthroughs in the fabrication of monolithically integrated devices.

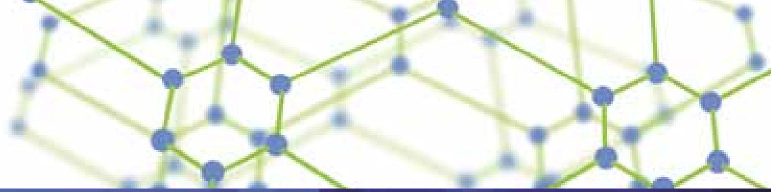
Replication of low-cost polymer-based nanophotonic components has received a great deal of attention recently. These components can be integrated with ALD-deposited films for obtaining new functionalities. This integration is possible since ALD is a low-temperature process. Interestingly, roll-to-roll ALD technology is emerging, which can lead to innovative low-cost fabrication technologies for integrated organic-inorganic photonic components.

Layered 2D materials for photonics

Layered two-dimensional (2D) materials are based on a single layer (or a few atomic layers) of crystalline materials. There is an increasing number of possible layered materials. Currently, the best-known layered 2D material is graphene, where the carbon atoms are arranged in a 2D hexagonal honeycomb crystal lattice structure. Graphene has received significant scientific and technological attention since 2004, when it was mechanically isolated into single atomic layers. The 2010 Nobel Prize in Physics was awarded to Andre Geim and Konstantin Novoselov for their groundbreaking work with the first 2D material graphene. In a short time, several new applications of graphene have been demonstrated, based on its unique electrical, mechanical and optical properties. However, the absence of a bandgap restricts the use of graphene in many important applications, including several structures and devices for photonics.

The recent emergence of other 2D-layered materials beyond graphene has created stimulating expectations for research and potential applications thanks to their fascinating new properties. These layered 2D materials similar to graphene include the transition-metal dichalcogenides (e.g. molybdenum disulphide MoS_2, tungsten disulphide WS_2 and niobium diselenide $NbSe_2$), group-IV metal chalcogenides (e.g. SnSe) and other 2D compounds (e.g. hexagonal boron nitride h-BN).

These new layered materials exhibit diverse properties. Hexagonal BN, a layered material closest in structure to graphene, is an insulator, while SnSe and monolayer



MoS_2 are direct bandgap semiconductors and $NbSe_2$ is metallic. An additional modification to the properties is obtained by stacking different layered materials to form nanolaminates or hybrid materials. For example, sandwiching a metallic single-layer graphene between two h-BN single layers opens a bandgap in graphene making it semiconducting. The diverse variable properties of the 2D-layered material systems offer a huge potential for both research and technological applications ranging from photonics to energy-harvesting sensors.

The development of new layered materials for photonics has been severely hampered by the lack of fabrication methods that produce high-quality material in sufficiently large quantities. This is analogous to the rapid increase in interest in graphene research when the simple method to mechanically exfoliate graphene from graphite (the ‘Scotch tape’ method) was replaced by more advanced crystal-growth techniques. The basic properties of the materials can be demonstrated by using small micron-scale exfoliated flakes, but especially many optical devices require considerably larger areas of materials.

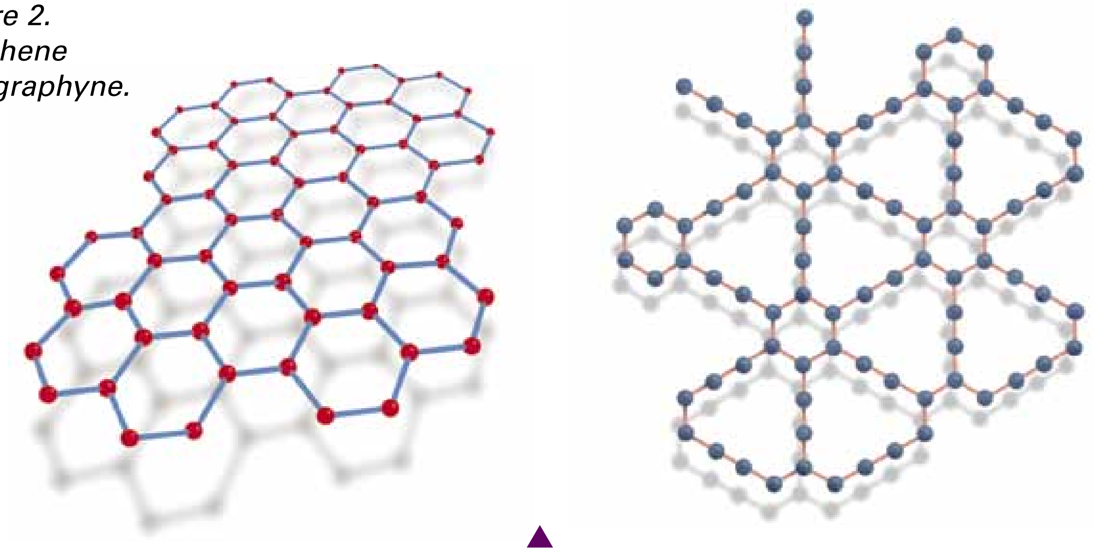
Although photonics with new 2D materials is still largely unexplored, the potential of these materials can be forecasted to be extremely high. The applications of new layered 2D materials arise from their extraordinary material properties. For example, because of the lack of a direct bandgap in a single layer graphene, it is not suited for light emission. MoS_2 and WS_2 monolayers, however, can emit light – and even far more efficiently compared to bulk material. This shows their huge potential for efficient light generation and amplification in active optoelectronic devices.

New materials for photonic components

Future advances in photonics rely on the integration of optics with new materials and structures that can operate in regions of the electromagnetic spectrum not currently covered. The mid-infrared wavelength range from 2 to 20 microns is a spectral region of tremendous interest, as it contains the characteristic vibrational transitions of many important molecules. This makes it strategically important for a wide range of applications ranging from chemical and biosensing to spectroscopy and thermal imaging. The relatively transparent atmospheric transmission window in the mid-IR range is also very attractive for industrial and military applications, such as remote sensing and explosive detection or free-space communication systems.

Light sources operating in the mid-IR range are facing a considerable challenge and their current

Figure 2. Graphene and graphyne.



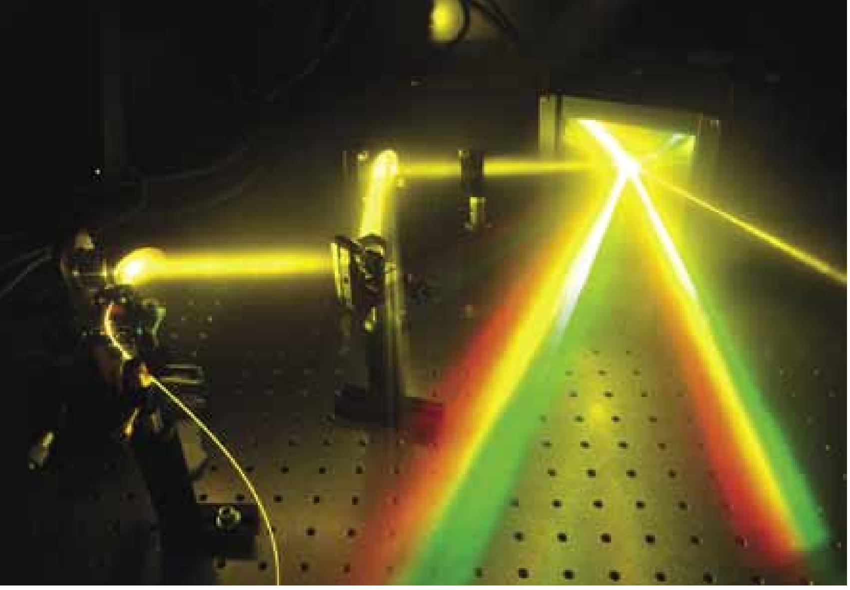


Figure 3.
Supercontinuum generation with an optical fibre.

availability has yet to match that of lasers operating in the visible or near-infrared range. Yet, the development of mid-IR sources is central to the emergence of mid-IR photonics applications and quantum cascade lasers made of special semiconductors alloys or fibre lasers that use host materials for thulium, holmium or erbium rare-earth ions and that are capable of producing short pulses with high optical power is thus paramount.

Optical fibres are widely used to convey light from metre-to-kilometre distances. Optical fibres are traditionally made of silica and can transmit light in the visible and near-IR region of the electromagnetic spectrum because of the low attenuation of the material in this range. However, the large absorption of silica outside this region prevents the transmission of light at other wavelengths, and fibres that are capable of guiding light in the mid-IR range and beyond represent an important step for the development of mid-IR photonics. Promising candidate materials include silicate, fluoride, or chalcogenide glasses. Today, the fabrication of robust optical fibres with these materials still remains difficult, and vast research efforts are needed to match the performance of conventional silica fibres.

Over the last few decades, Finland has gained significant expertise in fabrication of optical fibres and fibre-based devices. In addition to academic players, we have several high-tech companies working in the field. In the future, there will be a high demand for new types of telecom fibres and other specialty fibres, for applications such as sensors and materials processing. New fabrication technologies play a crucial role in developing novel optical fibres based on new materials. With the vast know-how in optical fibre technology, this is a great opportunity for Finland.

Another important direction for future photonics applications is the development of materials compatible with the standard CMOS technology that underpins the fabrication of modern integrated circuits. This will open up new avenues for the implementation of hybrid devices that integrate electronic and optical components into a single chip. Along with the development of silicon photonics, which is the most advanced solution towards the realisation of optical interconnects for fast data transfer between microchips, wide-bandgap materials (e.g. silicon nitride, silicon carbide, gallium nitride and aluminium nitride) could pave the way for the shortcomings of silicon photonics in terms of nonlinear losses and free carrier interactions. So far, the use of such materials has been limited as little is known about their optical responses, and a significant research effort could boost the progress towards the realisation of hybrid integration and optical components with novel functionalities.

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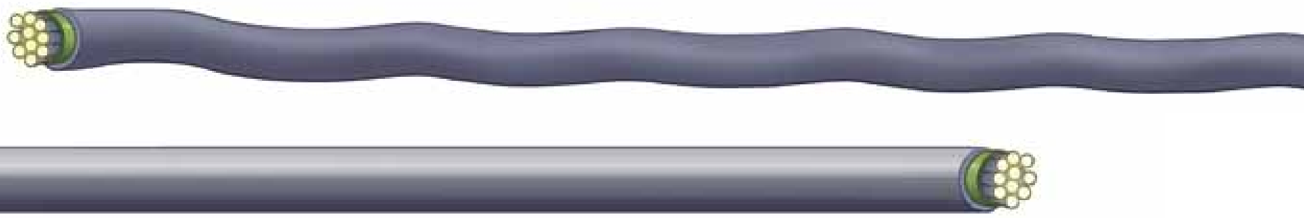

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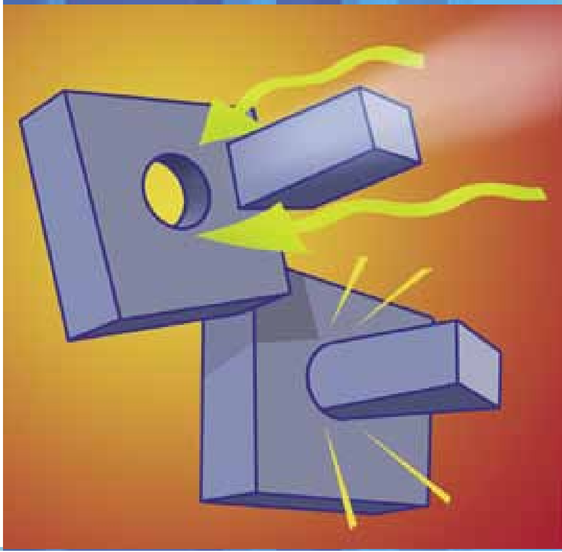

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