



ICT Sector Focus Report

Nanophotonics for optical communications

April 2010

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1 Executive summary

Nanophotonics describes the study of the behaviour of light at sub-wavelength scales. The purpose of this report is to present nanophotonic technologies and structures that may be used for high performance optical communication devices. A major part of this report focuses on an area of optical communications called optical interconnects that might replace traditional electrical interconnects in the future in many applications.

Optical links have been used for many years in wide area networking and they are finding their way to shorter and shorter links. Short range optical links, for on-chip and chip-to-chip communications, are typically called optical interconnects. There are many physical advantages of using them instead of electrical interconnects. There are still huge challenges related to optical interconnects including component performance and reliability, integration and manufacturing.

This report will mainly focus on different nanostructures that can be used for enhancing the performance of components used in optical interconnects and optical communication systems. The components include transmitters, receivers and optical media such as waveguides. The nanostructures described and assessed in this report are:

- Quantum wells in III-V materials
- Quantum dots in III-V materials
- Quantum wells in Silicon
- Quantum dots in Silicon
- High index contrast structures
- Surface plasmon polaritons

Figure 1, based on interviews and a web-based questionnaire of 28 experts, summarises the technological readiness level (TRL) and technology impact for these 6 nanostructures. Two of the structures assessed, III-V quantum wells and high index contrast structures are already very close to entering the markets whereas other nanostructures will require a significant amount of research and development before they can be commercialised.

Based on expert feedback, some products for long distance communication taking advantage of different nanostructures are already in the market and within a few years commercial board-to-board and chip-to-chip solutions will be available. On-chip optical

interconnects are still in a very early stage of development and they will be expected to reach the market in 5-10 years at the earliest.

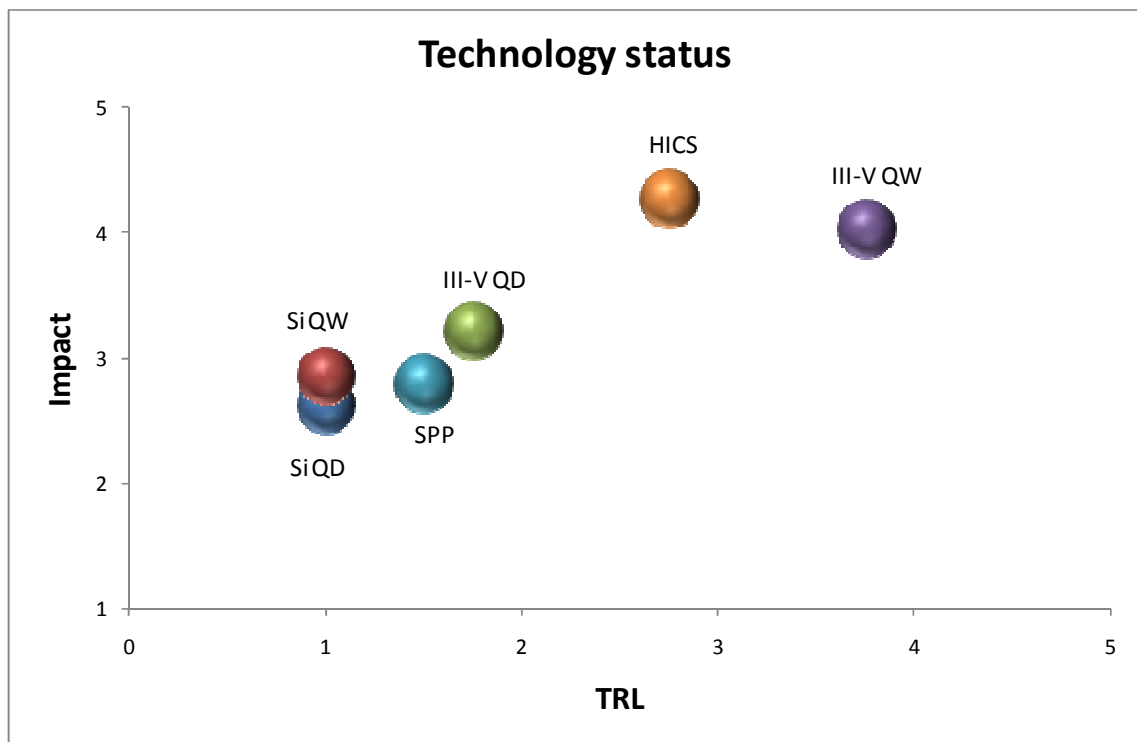


Figure 1 The current status of selected optical interconnect technologies. III-V quantum wells and high index contrast structures are the most mature technologies and are close to reaching markets, as well as possessing the highest impact. The other technologies are still in the applied or fundamental research phase and do not have a significant impact. TRL scale: 1) fundamental research 2) applied research 3) prototype 4) market entry 5) mature markets. Impact scale: 1) very low 2) low 3) neutral 4) high 5) very high

2 Introduction

2.1 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 the 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 on applications of nanophotonics for optical communications. The area of optical communications can be roughly divided in two subparts, traditional optical communications for long distance links and the emerging field of short optical interconnects. Even though both areas are very different from a component and system size point of view, they share many similarities in the lower levels of systems and therefore benefit from the same nanophotonic structures.

In principle, both long distance optical link systems and very short distance optical interconnects consist of the same basic components: a transmitter including a light/laser source and optical modulator, an optical medium (fibre for long links, waveguide for optical interconnects) and a receiver consisting of a photo detector and trans-impedance amplifier. In addition to these basic components, both systems may include, among others, wavelength division multiplexing (WDM) components, coupling structures, optical switches and amplifiers.

The major part of this report focuses on the optical interconnects for on-chip and chip-to-chip links. The physical requirements for these very short distance links are very high and therefore the area is more challenging for applying different nanostructures and technologies. Moreover, the same nanostructures and technologies that are applied to

nano-scale and micro-scale optical interconnects can typically be applied in discrete components for long distance optical links, too.

The motivation for replacing traditional electrical interconnects with novel technology is the fact that the electrical interconnects do not scale to keep up with digital information processing devices. Electrical interconnects have already been replaced by optical links in wide area networking because the losses in electrical wires are too high and sufficient transmission rates cannot be reached with them. Currently, electrical interconnects inside computer systems carrying information from one part of the system to another run at much lower data rates than the clock rate on chips because of the physical limits of electrical interconnects, which is an issue that could be solved by using optical interconnects.

In this report, we present different technological alternatives for replacing traditional electrical interconnects and assess their technological readiness and impact for ICT applications.

2.2 Overview

There are multiple competing technologies to replace electrical interconnects. The options include extensions to traditional copper-based (Cu) technology, replacements for copper and native device interconnects. The following list of emerging interconnects has been suggested in ITRS (International Technology Roadmap for Semiconductors) 2009 Winter Conference¹:

Option	Potential advantages	Primary concerns
Other metals (W, Ag, silicides)	Potential lower resistance in fine geometries	Grain boundary scattering, integration issues, reliability
Nanowires	Ballistic conduction in narrow lines	Quantum contact resistance, controlled placement, low density, substrate interactions
Carbon nanotubes	Ballistic conduction in narrow lines	Quantum contact resistance, controlled placement, low density
Graphene nanoribbons	Ballistic conduction in narrow films, planar growth	Quantum contact resistance, control of edges, deposition and stacking
Optical (interchip)	High bandwidth, low power and latency, noise immunity	Connection and alignment between die and package, optical/electrical conversions

1

http://www.itrs.net/Links/2009Winter/Presentations/Conference/3New%20Interconnect%20Presentation%20Hsinchu%2016%20Dec%202009_v5.pdf

Optical (intrachip)	Latency and power, reduction for long lines, high bandwidth with WDM	Benefits only for long lines, need compact components, integration issues, need WDM
Wireless	Available with current technology, wireless	Very limited bandwidth, intra-die communication difficult, large area and power overhead
Superconductors	Zero resistance interconnect, high Q passives	Cryogenic cooling, frequency dependent resistance, low critical current density

A classification scheme by Tummala & Rymaszewski (1989) based on interconnect length and type of interconnected components is listed below². The emphasis of this report is mainly in intra-chip (or on-chip) and chip-to-chip levels.

- Chip level (intra-chip) 0...10 mm
- Multi-chip-module level (intra-MCM or chip-to-chip) 1...100 mm
- Board level (MCM-to-MCM or chip-to-chip) 10...300 mm
- Backplane level (board-to-board) 0.1...1 m
- Cabinet level (rack-to-rack) 0.3...5 m
- System level (cabinet-to-cabinet) 1...100 m

The list below contains the nanostructures and technologies that are discussed in this report. A web-based questionnaire was conducted as part of the study including both multiple choice questions for selected nanostructures and open-ended questions. Multiple choice questions were used to assess the technological development stage and impact of the nanostructures. Structures marked by an asterisk (*) were included in the questionnaire.

- Structures based on III-V materials
 - o Quantum wells or QWs*
 - o Quantum dots or QDs (nanocrystals)*
- Structures based on silicon
 - o Quantum wells*
 - o Quantum dots*
- High index-contrast structures*
 - o E.g. photonic crystals
- Plasmonics
 - o Surface Plasmon polaritons*
- Other

² Mikko Karppinen: <http://www.vtt.fi/inf/pdf/publications/2008/P698.pdf>

- Ge/SiGe based technologies
- Metamaterials

The most prominent application area for optical interconnects is data communications and telecommunications equipment. This is because optical communication over fibres has been already used for long and optical interconnects are therefore a natural extension to that technology (e.g. all-optical signal processing). Other potential application areas include high performance computing and backframe computers. To some extent, microprocessor chips in personal computers might benefit from using optical interconnects but it will take probably more than 10 years for optical technology to replace electrical interconnects in these low-end systems.

2.3 Methodology

2.3.1 Basic components

In typical electrical systems, interconnects are directly connected to the logic circuits. However, optical interconnects systems require multiple components for electrical-to-optical and optical-to-electrical signal transformation as well as for guiding and routing the signal from optical transmitter to optical receiver.

The main components of an optical interconnect system are presented in the following list and their relationship can be seen in Figure 2:

- Transmitter
 - Laser source
 - Optical modulator (electrical-to-optical)
- Receiver
 - Photo detector (optical-to-electrical)
 - Trans-impedance amplifier
- Routing
 - Waveguide
 - Optical switches
 - Couplers
- Multiplexing/demultiplexing (WDM) (optional)

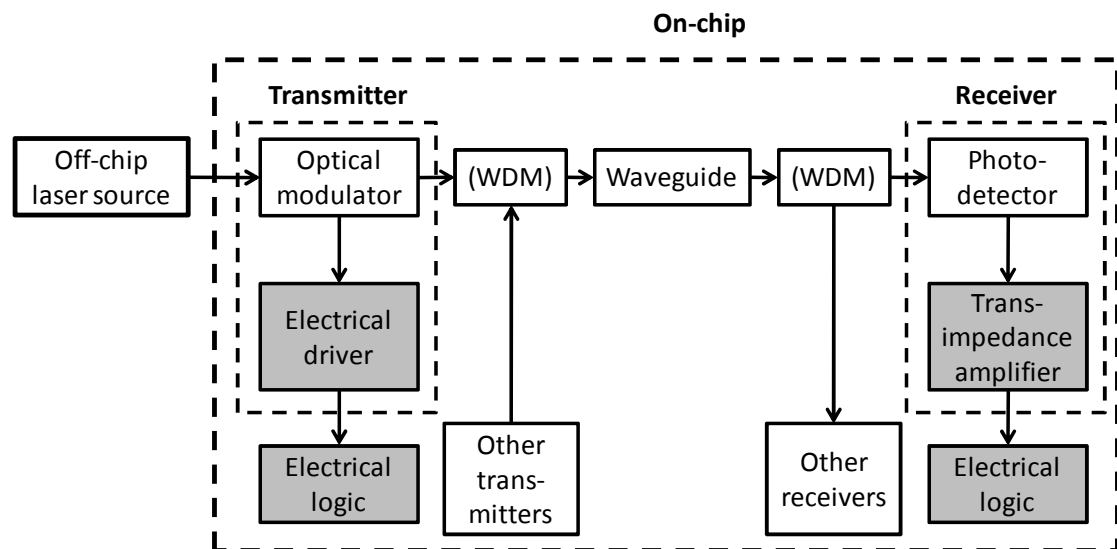


Figure 2 Basic structure of optical interconnects system. All components except WDM are integral parts of optical interconnect systems. The use of wavelength division multiplexing is optional although it is a powerful method for increasing optical interconnect system data rate. Figure adapted from http://www.enqr.colostate.edu/~sudeep/pubs/publications/IPSJ_pasricha_Sep08.pdf

Laser sources are an integral part of optical interconnect systems because they produce the light that is later processed in many ways by different components in order to transmit data over the optical medium. Optical interconnect systems may use either off-chip or on-chip laser sources. Off-chip laser sources are generally easier to manufacture and they can be even replaced in case of a faulty component. As they are not located inside the chip, they are not part of the chip's power or heat budget making the chip design easier on those aspects. The downsides of using off-chip laser sources are that they require multiple coupling structures to route the light inside the chip and the off-chip structure needs its own packaging and its location needs to be taken into account in the system level design. On-chip laser source does not have the coupling issues and it is naturally integrated inside the chip. The challenges of on-chip solutions relate to integration of components, higher power requirements, higher heat generation and reliability of the integrated component.

The optical modulator is a component that is responsible for transforming the electrical signal to an optical signal. The modulator component has two inputs, one from the laser source (the signal to be modulated) and another from the electrical logic cell (the modulating signal). The modulator transforms the light coming from the laser source into light pulses according to the bit sequence it receives from the electrical logic cell.

After the optical information signal has been generated, it is channelled into the optical routing structure. The media used in optical interconnects are called waveguides, which are typically dielectric materials with high index of refraction surrounded by a material with lower permittivity. Optical couplers are structures that are used to inject the light into the optical system, e.g. in the case of an off-chip laser source. Optical switches are used in optical routing networks to route the light travelling in waveguides to different locations inside the chip.

The receiver side of the optical interconnect system performs inverse operations compared to the transmitter. A photo detector is responsible for detecting the light pulses arriving via the waveguide and reconstructing the electrical signal. A trans-impedance amplifier is finally used for amplifying the electrical signal to a level on which it can again be routed to electrical logic cell.

Wavelength division multiplexing (WDM) is a method for achieving higher data rate in optical systems without developing higher performance transmitter or receiver components. Because of the nature of light (and electromagnetic waves in general) several signals can travel in a single medium as long as their wavelength bands (frequency for RF communications) do not overlap. In case of optical interconnects this means that multiple signals can use a single waveguide at the same time if their wavelengths are different. WDM components are not an essential part for optical interconnect systems but they are considered very important in order to build high performance optical interconnects that can compete with electrical interconnects.

2.3.2 Nanostructures and technologies for optical interconnects

A quantum well is a thin layer which can confine particles in one dimension perpendicular to the layer surface. The particle movement in the other dimensions is not restricted. Quantum well makes the density of the states for the confined particles higher which a favourable effect for many active optical components.

A quantum dot is a structure which can confine electrons or other carriers in three dimensions. The carrier confinement is a quantum effect that changes the density of states for confined particles. Quantum dots have multiple applications in lasers, LEDs, photo detectors and perhaps in quantum computing.

In high index contrast structures, the difference between the highest and lowest refractive index of a device should be as high as possible. This can be achieved by using a combination of a semiconductor material with a low index dielectric, for example. High index contrast allows for strong confinement and makes it possible to build ultra-compact optical devices.

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.

3 Science and Technology Aspects

3.1 State of R&D

3.1.1 Physical differences between electrical and optical interconnects

Although both electrical and optical signals are carried by electromagnetic waves, the physics behind them are very different. Based on physical properties, optical interconnects have many potential benefits to offer. The main physical advantages of optical interconnects (OIs) have been reported in multiple papers (e.g.³):

- **Very high carrier frequency up to 1000 THz (tens of GHz for EIs)**
 - High-speed modulation of optical beams makes no difference in propagation of the beam
 - Makes long lines with high data rates possible
- **Short wavelength of light**
 - Dielectric waveguides with very low loss can be used
- **Large photon energy in optics**
 - Leads to voltage isolation
 - Optical links could save interconnect power
- **Very precise timing in clocks and signals**
 - No substantial spread of signal for distances used in interconnects

These physical properties of optical interconnects mean that they can achieve enormous data bandwidths even with simple modulation schemes. Optical communications is also almost immune to electrical interference due to crosstalk and parasitic capacitances and inductances, which are a significant issue in the further development of electrical interconnects for higher frequencies. Because of the properties of light, it is possible to physically intersect light beams with minimal crosstalk. This advantage of optical interconnects would simplify signal routing and component placement in chips.

However, there are also some fundamental challenges related to optical interconnects on various levels that need to be solved before they can be credibly used for complementing or replacing electrical interconnects (EIs). If optical interconnects are to challenge electrical

³ <http://ee.stanford.edu/~dabm/370.pdf>

interconnects, high speed, low power and small feature-size components need to be developed.

Power dissipation is a major challenge for all interconnects because more than 50% of microprocessor power is consumed by the interconnections and the figure is expected to rise up to 80%. For optical interconnects to be successful, they need to consume less power than their electrical counterparts. According to D.A.B Miller⁴ the system energy per transmitted bit should be as low as 30 fJ/bit (femtojoules). The energy consumption of current electrical interconnects is around 2-30 pJ/bit (picojoules) and this figure is expected to go as low as 80 fJ/bit (1 pJ = 1000fJ). Therefore, optical interconnects need to be much better on energy consumption than their electrical counterparts.

Optical interconnect components are also very sensitive to temperature variations⁵. This is especially an issue in on-chip interconnects and temperature management issues need to be solved for optical interconnects to be successful.

Due to physical reasons, electrical interconnects perform better for short range links whereas optical interconnects become more competitive as the length between transmitter and receiver increases. In their paper on on-chip copper-based vs. optical interconnects Chen et al. suggest that optical interconnects are in general better than electrical interconnects when the length of interconnect is longer than 10% of the chip edge length⁶.

The general opinion is that optical interconnects will be very much needed in optical interconnects, especially in chip-to-chip and longer links. However, it is still unclear if the technology will ever be competitive enough for on-chip optical interconnects. Even though optical interconnects components can be manufactured without application of nanostructures such as quantum wells or high index contrast structures, these structures are needed in order to facilitate higher states of integration and therefore smaller and lower cost devices. Additionally, the application of different nanostructures will enhance the functionality and performance of optical interconnects components.

⁴ <http://www-ee.stanford.edu/~dabm/370.pdf>

⁵ http://www.engr.colostate.edu/~sudeep/pubs/publications/IPSJ_pasricha_Sep08.pdf

⁶ http://www.ece.rochester.edu/users/friedman/papers/IIT_06.pdf

Basically all components in optical interconnect systems (Figure 2) can benefit from these nanostructures. Quantum well and quantum dot structures will enhance the performance of active components such as light sources (lasers), modulators and photo detectors. On the other hand, high index-contrast structures and surface plasmon polaritons will have an impact in passive components such as waveguides but on active components, too.

The main advantage of the nanostructures listed above is that they can be used to increase the efficiency and performance of optical components. This results in better performance in discrete components used in long distance links but also makes it possible to manufacture very small components with good performance to be used for very short optical interconnects. A higher level of integration will also, eventually, make all-optical signal processing possible, which brings cost reduction for long lines and makes use of very short optical links possible.

There are many potential candidates for technologies to be used in optical interconnects and therefore it is not likely that all of them will be used in the final applications. Most potential candidate technologies are addressed later in section 3.3.

However, when optical interconnects finally gain ground in the market, combination of various technologies will most likely be applied. Possible combinations suggested by the experts interviewed could be photonic crystals with embedded quantum dots or quantum wells with plasmon waveguides.

3.1.2 Nanostructures based on III-V materials

Semiconductors based on III-V materials are widely used for various active optoelectronic components. III-V material technology itself is mature and nanostructures, e.g. quantum wells, based on III-V materials have already been manufactured and are quite ready for practical applications.

Quantum wells, and quantum dots to some extent, are the most efficient methods known for light generation and therefore their impact in laser sources is high. Nanostructures based on III-V materials could also be critical to reprogrammable interconnects. Nonlinear optics is also an interesting area for application of III-V material based nanostructures.

The largest factor inhibiting the technology success of III-V materials is their incompatibility with silicon-based integrated circuits. This issue needs to be solved for III-V materials to find their way into mass-manufactured integrated circuits.

3.1.3 Nanostructures based on silicon

In principle, silicon based nanostructures would be a natural choice to be used in optical interconnects because most of today's integrated circuits are silicon based. However, the situation of silicon based optical interconnects is still very unclear and silicon needs to be demonstrated as an efficient optoelectronic material.

In case silicon proves to be an adequate optoelectronic material, silicon based nanophotonics would provide many benefits over competing technologies such as nanostructures based on III-V materials. The largest benefit from using silicon-based structures would be the ease of integration as the silicon based structures are naturally compatible with silicon based CMOS manufacturing. Silicon can in principle be used for all main components required for optical interconnects: active components with quantum wells or quantum dots and passive components as such or enhanced with, for instance, photonic crystals or other high index-contrast structures.

Apart from silicon, other Group IV based semiconductors are very promising for use in optical interconnects. Ge/SiGe materials employing quantum confined Stark effect (QCSE) might have great potential in modulation and detection components.

On March 4th 2010 IBM announced that they have developed a nanophotonic germanium avalanche photodetector, which is capable of receiving optical information signals at 40Gbps. Between 2005-2008, IBM has developed a series of inventions in silicon photonics: reducing the speed of light (i.e. slow light), a compact optical buffer with ring resonators, an ultra-compact optical modulator and a high-throughput nanophotonic switch. These devices bring on-chip optical interconnects one step closer and IBM, Sony and Toshiba are currently planning to integrate them on a Cell microprocessor chip.

3.1.4 High index-contrast structures

High index-contrast structures are beneficial for all optical interconnect components. They offer the benefit of slow light which aids in switching, routing, frequency conversion and other processing steps and they are also suitable for developing higher performance

waveguides. High index-contrast structures also have benefits in transmission and receiver components, making them the most versatile nanostructures considered in this report.

According to experts, high index-contrast structures are very much needed in the development of higher performance optical interconnects and the technology is already mature enough to be implemented. Some discrete products utilising these structures are already on the market by providers such as Luxtera, Kotura and Lightwire. They are suitable to be used in monolithic integration with silicon and therefore a very potential technology for optical interconnects components and their integration.

3.1.5 Plasmonics

Surface plasmon polaritons are a technology that has ICT application potential in subwavelength optics. They can be used to confine light to smaller areas and volumes compared to Si-based waveguide technology and they have also been used to drive nonlinear optical processes which may lead to new applications in future. The area of plasmonics is still in very early development stage and therefore its applications are yet quite unclear.

Some proof of principle and isolated devices utilising surface plasmon polaritons have been build and they can be used in both active and passive optical interconnects components such as photodetectors, modulators and waveguides. They may also aid efficiency of classical light sources. At this very early phase of research, they are thought to have large potential for more exotic applications such as quantum computing because plasmonic technology can be used for building quantum light sources for single photons.

3.1.6 Challenges

There are numerous challenges currently inhibiting the market entry of optical interconnects. These technological challenges are mainly related to costs, components, integration and manufacturing. The following list summarises the key challenges suggested by the experts:

- Technology development related
 - o Cost of technology development
 - o Lack of collaboration between research organisations and industry
- Component related

- Reliability of nanotechnology/nanostructures
- Performance issues of optical interconnects components
- Size of components
- Heat variations (especially on-chip)
- Lack of nanoscale lasers and all-optical switches
- Power consumption
- Integration related
 - Compatibility of nanotechnology and CMOS technology
 - How will optical interconnects handle the use of 3D designs
 - Coupling structures (especially off-chip)
 - Monolithic integration of active optical components on electronic chips at reasonable cost
- Manufacturing related
 - Yield in manufacturing processes
 - Difference in lithographic techniques between electronics and optical interconnects
 - Manufacturing accuracy
 - Packaging

The long list shows that significant amount of technology development for both nanostructures and optical interconnect technology in general is required if the technology is ever going to complement or replace the traditional electrical interconnects. Much component level development and system level optimisation needs to be done in order to prove the potential and benefits of optical interconnects.

3.2 Additional demand for research

Based on the list on the Challenges section, a large amount of additional research is needed for the optical interconnects to be able to challenge electrical interconnects. Naturally, a large challenge for optical interconnects is the cost of technology development. Much of optical interconnects research is conducted in universities and technology centres around the world. These organisations typically do not have access to state-of-the-art integrated circuit fabrication equipment which makes it very difficult to study how optical interconnect components could cost effectively be mass manufactured. This means that there is a limited number of companies in the world that are able to solve the issues of mass manufacturability of optical interconnects for integrated circuits. Moreover, researchers

consider that a lack of organised effort, required commitment and collaboration between industry and scientists is a significant barrier that is slowing down technological development.

The development of optical interconnect components themselves is an area in which a lot of research is conducted by universities and research organisations as the manufacturing equipment requirements are much lower. The greatest challenge related to components is the sheer performance (bit/s, pJ/bit, etc.), the size of the components and their reliability. Performance and reliability issues need to be solved before optical interconnects can really challenge electrical interconnects. The size of components is closely related with the power consumption and the heat production of the circuit; the smaller the components are the less power they consume and the less heat they generate. Novel components, such as nanoscale lasers and all-optical switches are also required for manufacturing higher performance systems with integrated optical interconnects.

In addition to component performance, there are some integration issues to be solved before optical interconnects can be used for replacing electrical interconnects especially in on-chip configurations. The largest challenge is the compatibility of nanostructures (e.g. III-V materials) with currently used CMOS technology. The design methodologies of integrated circuits need to be developed further so that optical interconnects can be a natural part of the circuits and can replace electrical interconnects gradually. The photonic layer can be integrated in circuits by 3 different ways: at the same level as the transistors (front end), above the integrated circuit in-between the metallic interconnection layers or manufacturing the photonic devices separately and bonding them to the IC. Specifically for chip-to-chip optical interconnects and on-chip optical interconnects with off-chip lasers, the development of lower loss and better performance coupling structures is needed to guarantee that most of the energy of the optical signal is retained in interfaces between different media.

Finally, a significant amount of research and development is needed regarding manufacturing methods in order to economically manufacture optical interconnect systems. Currently, the largest challenge is perhaps that electrical and optical interconnects require different lithographic techniques which is naturally a large barrier to introduction of optical interconnects. Moreover, due to technical and economic reasons both manufacturing accuracy and yield need to be improved. Packaging corresponds to a major part of integrated circuit manufacturing costs and therefore the costs of packaging integrated

circuits using optical interconnect technology should be on a level of packaging systems using only electrical interconnects.

3.3 Applications and perspectives

3.3.1 Technological development stage and technology impact

The figures presented in this section are based on a quantitative assessment of a questionnaire that was targeted to a group of experts studying or working with optical interconnect technology, to which 25 of them responded. The figures offer a summary of technology developmental stage by combining the technology readiness level (TRL) and the estimated impact of each technology.

For simplicity the following abbreviations are used for the technologies assessed:

- III-V QW = Quantum wells in III-V materials
- III-V QD = Quantum dots in III-V materials
- Si QW = Quantum wells in silicon
- Si QD = Quantum dots in silicon
- HICS = High index contrast structures
- SPP = Surface plasmon polaritons

The experts assessed the technology readiness level of each of technology based on several questions. The different technology levels are defined as follows:

- **TRL1: Fundamental research:** Physical laws and phenomena behind this structure is known and critical challenges regarding the application of structures are known.
- **TRL2: Applied research:** Proof-of-concept components utilising these structures are manufactured, integration is still a challenge
- **TRL3: Prototype:** Functional prototypes (e.g. integrated circuits) having components utilising these structures are manufactured.
- **TRL4: Market entry:** First products utilising these structures have entered the markets
- **TRL5: Mature markets:** Multiple vendors are providing products and technology utilising these structures

The assessed impact is the current status of technologies listed. We assessed five aspects and the impact is the average of these:

- Manufacturability of the nanostructure
- Performance of the components using listed nanostructures
- Cost effectiveness of manufacturing components using listed nanostructures

- Reliability of components using listed nanostructures
- Performance of the manufacturing process for listed nanostructures

Based on the respondents answers to above questions the impact is classified using as follows: 1) Very low 2) Low 3) Neutral 4) High 5) Very high

In Figure 3 two technologies clearly stand out from the rest. III-V quantum wells are considered the most mature technology which is already entering the market. High index contrast structures is on a general level entering the prototype phase, which means them being integrated in various chip configurations. There are, as stated before, already some HICS based products on the market but these are currently discrete components.

The rest of the technologies are still in either fundamental research or applied research phase. Significant amount of research and development is required for solving the largest challenges related to these technologies and for enhancing their performance. A linear dependence between TRL and technology impact can be seen in the figure. This represents the fact that silicon based technology, surface plasmon polaritons and III-V quantum dots still need to be proven to be effective technologies for optical interconnects. On the other hand, high index-contrast structures and III-V quantum wells already show clear benefits for optical interconnects and therefore their impact is considered high by the experts.

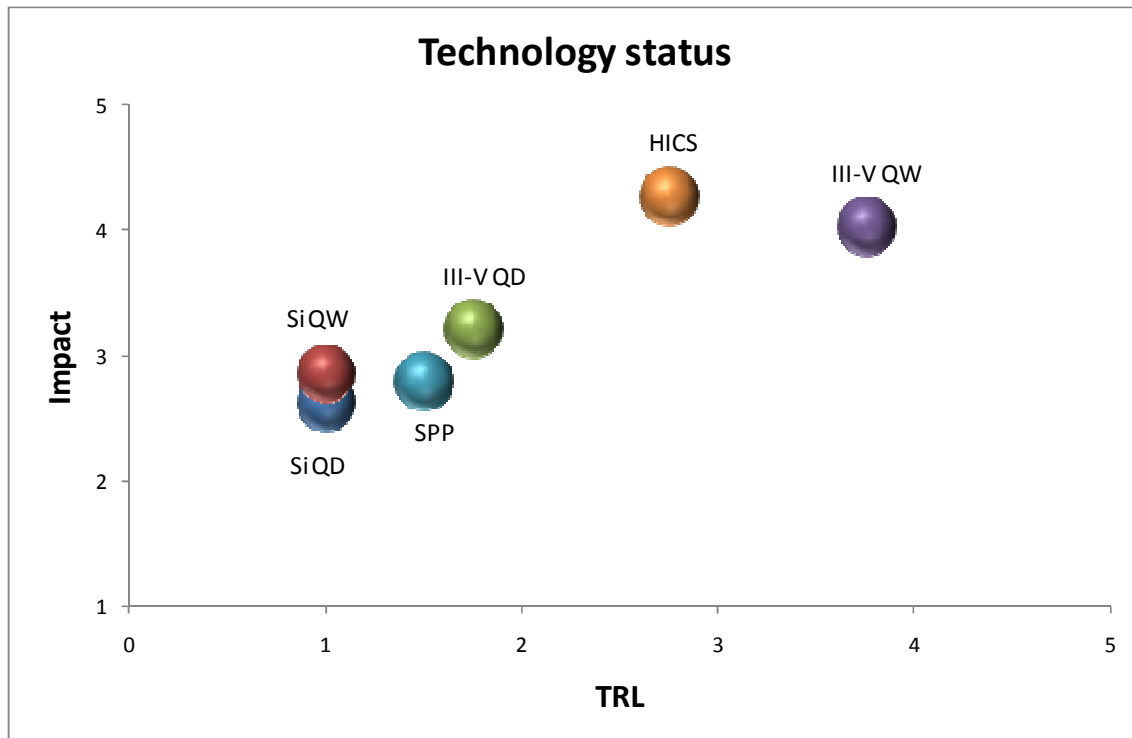


Figure 3 The current status of selected optical interconnect technologies. III-V quantum wells and high index contrast structures are the most mature technologies and are close to reaching the market which also possessing the highest impact. Other technologies are still in applied or fundamental research phase and do not have a significant impact. TRL scale: 1) fundamental research 2) applied research 3) prototype 4) market entry 5) mature markets. Impact scale: 1) very low 2) low 3) neutral 4) high 5) very high

Based on Figure 4, the most mature technology, III-V quantum wells, are already entering the markets. This means that they are being used in discrete components, board-level and chip-to-chip optical interconnects. Integration of III-V technology with silicon based CMOS technology is still difficult and this issue needs to be solved before III-V quantum wells can be applied in on-chip configurations.

High index-contrast structures are currently in transformation from applied research to building prototypes. Prototypes and even commercial products utilising these structures have been seen in discrete components but their integration in chip-to-chip and on-chip configurations still needs more development. A clear benefit of high index-contrast structures is that monolithic integration with silicon-based technology is possible. This basically means that after their performance has been proven in functional prototypes, their introduction in current manufacturing processes should be relatively easy. This can also be seen in the short market entry phase of HICS in Figure 4.

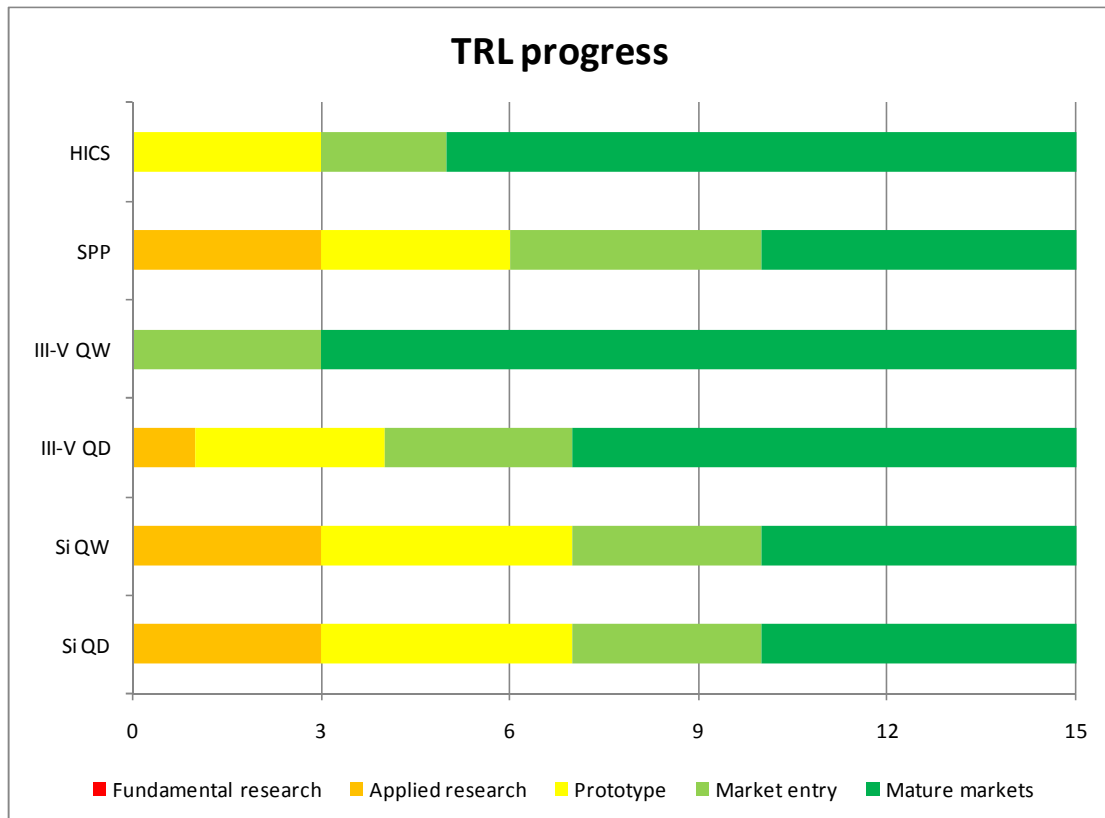


Figure 4 Future projection for selected optical interconnect technologies (this figure reflects the situation in off-chip optical interconnects, which are more mature than on-chip OIs). III-V quantum wells and high index contrast structures are considered the most mature technology. III-V quantum dots are to reach the market phase third of the selected technologies. The horizontal axis represents estimated years for reaching the TRLs listed.

All of the other technologies assessed are still in the fundamental or applied research stage. Even though they share similar challenges regarding integration, reliability and costs as high index-contrast structures and III-V quantum wells, a significant amount of research and development needs to be conducted in order to prove that their performance is on adequate level to be used in real applications.

Figure 5 shows a breakdown of different technology impact areas for technologies assessed in this report. When technologies are assessed from this perspective, the same conclusion can be drawn as from Figure 4 and Figure 5. High-index contrast structures and III-V quantum wells clearly have a positive impact for optical interconnects. III-V quantum wells clearly have a positive impact for optical interconnects. III-V quantum dots have a positive impact on some areas and a neutral impact on others. Silicon-based technology and surface plasmon polaritons have either neutral or low impact.

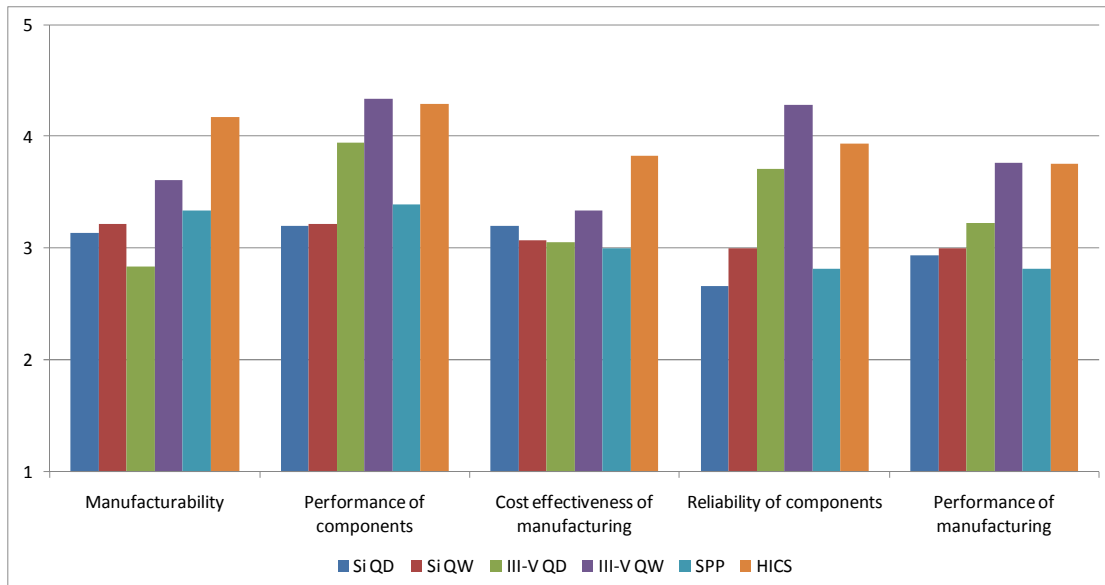


Figure 5 Breakdown of technology impact. III-V Quantum wells and high index contrast structures clearly outperform the other technologies, which impact is mostly considered neutral. Impact scale: 1) very low 2) low 3) neutral 4) high 5) very high

Based on these results, it is clear that the most potential technologies to be applied in optical interconnects are III-V quantum wells and high index-contrast structures. Other technologies require significant effort in technological development to be competitive with more mature technologies.

3.3.2 Applications

There are several different application areas for optical interconnect technologies presented in this report. Firstly, development in optical interconnect technology makes it possible to build all-optical signal processing which can be used in optical communications equipment such as routers, switches, amplifiers etc. Optical interconnects are a natural extension to optical communications equipment for long distance links because they have the benefit of creating end-to-end optical links. Technological development will lead to higher level of integration and eventually miniaturisation of components and cost savings.

Other large application areas for optical interconnects are high performance computers, backframe computers and supercomputers. The current trend in computing is multicore chips and computers that employ massive parallel processing. Parallel computing requires high data rate interconnects between chips and cores and therefore applying optical interconnects for these applications seems a natural approach. The demand for higher data rates is also a bottleneck for developing higher performance computers and therefore

optical interconnects will most probably be needed for solving this bottleneck in the next 5 years.

Personal computers and other lower performance computers are not currently that attractive an application for optical interconnects, as the performance demands of personal computers can be solved by extending current electrical interconnect technology, for instance by different design choices. The distances inside personal computer chips are still too short for optical interconnects to outperform their electrical counterparts.

Another more exotic application area for optical interconnect technologies is quantum computing, which makes use of quantum mechanical phenomena to perform operations on data. Quantum computers are very different from traditional computers but some of the presented technologies are capable of creating and treating quantum light and therefore they can be utilised in the development of quantum computers.

3.4 Current situation within the EU

3.4.1 Universities and research centres in Europe

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/>

Centre for Micro and Nanotechnology (Micronova),

<http://www.micronova.fi/>

3.4.2 Universities and research centres outside Europe

Halas Nanophotonics Group, Rice University,

<http://www.ece.rice.edu/~halas/>

Plasmonics Multidisciplinary University Research Initiative (MURI), Stanford University,

<http://brongersma.stanford.edu/plasmonmuri/>

3.4.3 Projects, industry associations, etc.

European Photonics Industry Consortium,

<http://www.epic-assoc.com>

<http://www.dynamo.tno.nl/opera/opera48.asp> (Research group database)

<http://www.dynamo.tno.nl/opera/opera46.asp> (Company database)

Virtual Institute for Artificial Electromagnetic Materials and Metamaterials,

<http://www.metamorphose-vi.org>

NanoPhotonics to Realise Molecular Scale Technologies (PhOREMOST), (this FP6 Network of Excellent ran from 2004-2006)

<http://www.phoremmost.org>

Merging Optics and Nanotechnologies (MONA),

www.ist-mona.org

MONA partners list,

<http://www.ist-mona.org/partners.asp>

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>

Photonic Integrated Circuits using Photonic Crystal Optics (IST-PICCO),

<http://intecweb.intec.ugent.be/picco/> (ran from 2000-2003)

International Technology Roadmap for Semiconductors

<http://www.itrs.net/home.html>

Wavelength Division Multiplexing Photonic Layer on CMOS (WADIMOS)

<http://wadimos.intec.ugent.be/>

4 Economic aspects

4.1 General market description

Based on recent studies on the area and our findings above, it is clear that optical interconnect technology employing nanostructures studied in this report is not yet ready for markets. Therefore, it is difficult to make any estimates on the market size for those technologies. On a general level, the markets are already mature for optical technology for long distance communications as well as discrete optical components for shorter distances (> 1 metre).

According to MONA technology roadmap (data originally from BCC Research and Strategies Unlimited) 2009 sales for photonic integrated circuits (very short range optical interconnects) were \$735 million and for data communications and telecommunications (longer distance links) were \$2 500 million. Market growth rates (CAGR) between 2006 and 2009 were 25% and 13%, respectively. A recent study by marketsandmarkets.com estimated the global silicon photonics market size at \$23.21 million with a growth rate (CAGR) of 105.3% from 2009 to 2014.

A comparison to the global semiconductor industry sales, which is more than \$200 billion in a year (according to Semiconductor Industry Association), shows that there is a large growth potential for optical interconnects technology if the technological and economic barriers can be overcome.

4.2 Drivers and barriers,

The drivers and barriers for optical interconnect technology have been discussed in detail in section 3. To summarise our findings, there is a clear need for optical interconnects on same period of time but currently the technological barriers are inhibiting the market entry.

The main driver for using optical interconnects technology is that the electrical interconnects cannot keep track of Moore's law infinitely. This trend is already clear in long distance links and increasing data rate requirements make optical technology competitive for shorter and shorter distances. The main physical advantages of optical interconnects over their electrical counterparts are:

- Higher carrier frequency
- Lower losses
- Little crosstalk

- Higher photon energy (compared to electrons)
- Very precise timing of signals

Despite the clear physical advantages, there are huge technological barriers to be overcome before optical interconnect technology can compete with electrical interconnects in reality. The performance and reliability of components need to be improved significantly. On the other hand, the size of components needs to be made smaller, which has a negative effect on performance and reliability. The main advantage of using the nanostructures listed in this report is that they can be used for manufacturing smaller components with high performance.

In addition to component performance, integration of components and manufacturing integrated circuits using optical interconnects requires significant research investments. Due to challenges in optical interconnect integration, IC manufacturers are putting much effort in developing electrical interconnect technology further in order to avoid the use of alien optical interconnect technology. The incompatibility of mature III-V semiconductor materials with current CMOS technology is a large barrier and developments in manufacturing technology are needed to guarantee economic production of reliable integrated circuits employing optical interconnects. The list below summarises the largest barriers inhibiting the market entry of optical interconnect technology:

- Technological
 - o Performance and reliability of components
 - o Incompatibility of optical and CMOS technology
 - o Manufacturing accuracy, performance and reliability
- Economic
 - o “Electrical interconnect technology is still good enough”
 - o Cost of new technology development
 - o Yield in manufacturing processes

In conclusion, optical technology will gradually gain ground in shorter and shorter interconnect distances as the data rate requirements grow. This requires significant amount of technological development and new innovations to make manufacturing and integration of smaller, more reliable and higher performance components possible. For most applications, optical interconnects will only be used for some links requiring the highest data rates. However, optical signal processing equipment is an interesting application area where all-optical integrated circuits could be successful.

5 References

5.1 List of experts who contributed



The questionnaire was answered by 28 experts around the world (locations can be seen in figure above). The report was sent for a peer review to the same group of experts.

Dr. Faiz Rahman, Semiconductor Materials and Devices Department of Electronics and Electrical Engineering, University Of Glasgow, United Kingdom. More info at:

www.elec.gla.ac.uk

Dr. Xue-Chao Liu, Nano-Silicon Group, Department of Physics, University of Warwick, United Kingdom. More info at: <http://www2.warwick.ac.uk/>

Prof. Zeev Zalevsky, School of Engineering, Bar-Ilan University, Isreal. More info at:

www.eng.biu.ac.il/en

5.2 Other references

RP Photonics Consulting GmbH: An Open Access Encyclopedia for Photonics and Laser Technology (<http://www.rp-photonics.com/encyclopedia.html>)

International Technology Roadmap for Semiconductors
(<http://www.itrs.net/Links/2007ITRS/ExecSum2007.pdf>)

[ITRS: New Interconnect Presentation 2009](http://www.itrs.net/Links/2009Winter/Presentations/Conference/3New%20Interconnect%20Presentation%20Hsinchu%2016%20Dec%202009_v5.pdf)

(http://www.itrs.net/Links/2009Winter/Presentations/Conference/3New%20Interconnect%20Presentation%20Hsinchu%2016%20Dec%202009_v5.pdf)

David A. B. Miller: Device Requirements for Optical Interconnects to Silicon Chips
(<http://www-ee.stanford.edu/~dabm/370.pdf>)

David A. B. Miller: Optical Interconnects to Silicon (<http://www-ee.stanford.edu/~dabm/210.pdf>)

David A.B. Miller: Rationale and Challenges for Optical Interconnects to Electronic Chips (<http://www-ee.stanford.edu/~dabm/205.pdf>)

L. Pavesi & G. Guillot (Eds.): Optical Interconnects, The Silicon Approach (<http://books.google.fi/books?id=Zu4A5VxNYZ4C&lpg=PP1&ots=i8SP6D41HR&dq=optical%20interconnects&pg=PR16#v=onepage&q&f=false>)

IBM: Silicon photonics for next generation computing systems (http://www.research.ibm.com/photonics/publications/ecoc_tutorial_2008.pdf)

Mikko Karppinen: High bit-rate optical interconnects on printed wiring board, Micro-optics and hybrid integration (<http://www.vtt.fi/inf/pdf/publications/2008/P698.pdf>)

S. Pasricha & N. Dutt: Trends in Emerging On-Chip Interconnect Technologies (http://www.engr.colostate.edu/~sudeep/pubs/publications/IPSJ_pasricha_Sep08.pdf)

Chen et al: On-Chip Copper-Based vs. Optical Interconnects: Delay Uncertainty, Latency, Power, and Bandwidth Density Comparative Predictions (http://www.ece.rochester.edu/users/friedman/papers/IIT_06.pdf)

MONA: A European roadmap for photonics and nanotechnologies (http://www.ist-mona.org/pdf/MONA_v15_190308.pdf)

Marketsandmarkets.com: Silicon Photonics (2009-2014), report description (<http://www.marketsandmarkets.com/Market-Reports/silicon-photonics-116.html>)

Semiconductor Industry Association: Industry Fact Sheet (http://www.sia-online.org/cs/industry_resources/industry_fact_sheet)