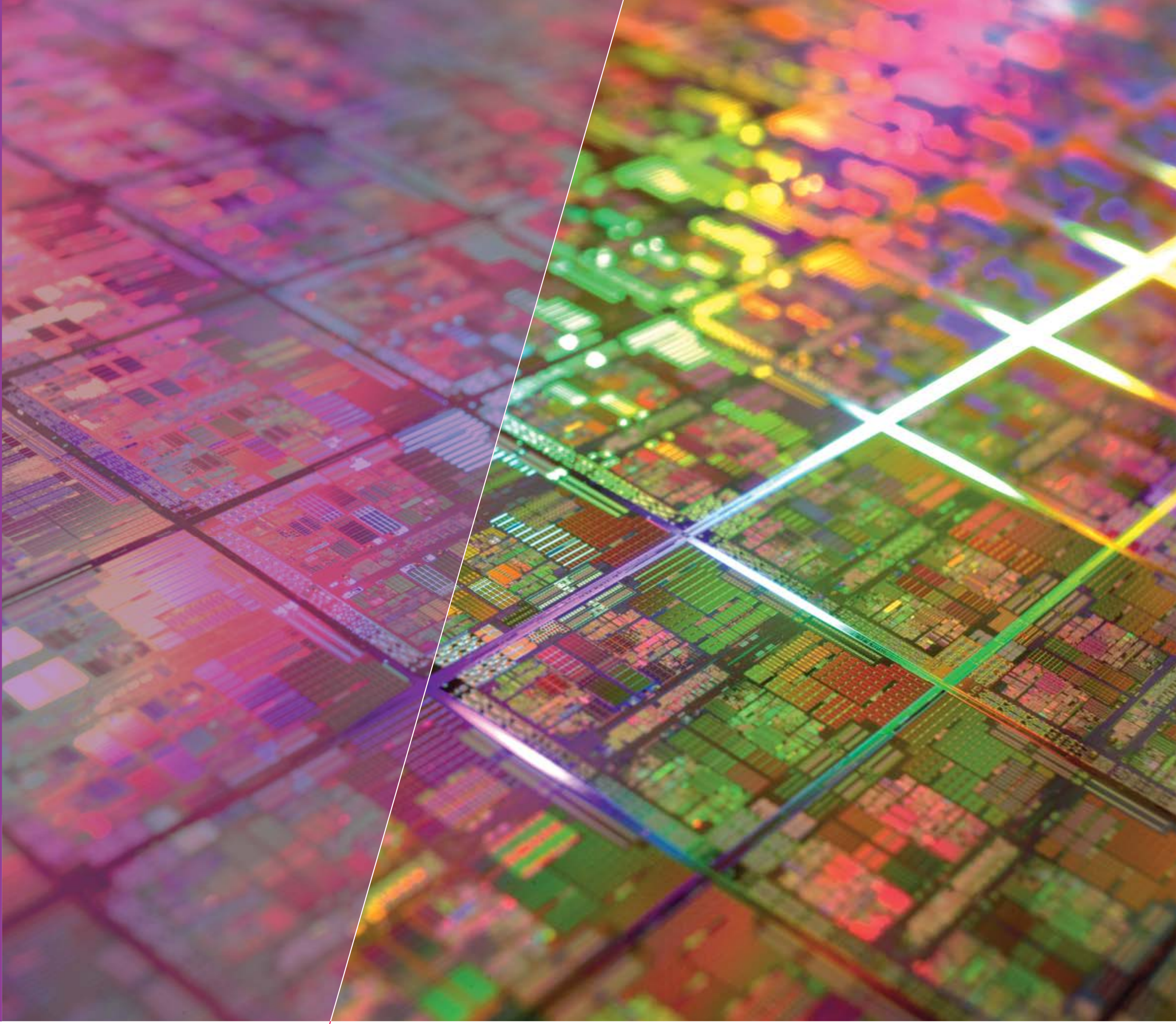

Research Centre for Integrated Nanophotonics

Annual Report 2014 & 2015

1 July 2016

Technische Universiteit Eindhoven
University of Technology

Institute for Photonic Integration
Materials • Devices • Systems

Research Centre for Integrated Nanophotonics

Annual Report 2014 & 2015

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Contents

Facts

Program	Gravitation (*Zwaartekracht*) 2013
Title	Research Centre for Integrated Nanophotonics
Number	024.002.033
Duration	10 year (January 1st, 2014 - December 31st, 2023)
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Prof.dr.ir. W.M.M. (Erwin) Kessels	Atomic Layer Deposition	PMP
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Prof.dr. K.A. (Kevin) Williams	Photonic Switching	PHI
Prof.dr. A. (Andrea) Fiore	Quantum Photonics	PSN
Prof.dr. E.P.A.M. (Erik) Bakkers	Semiconductor Nanowires	PSN
Dr. A.A. (Ageeth) Bol	Nano-Electronic Materials	PMP
Prof.dr.ir. G.C. (Gunther) Roelkens	Silicon Photonics	PHI

Executive summary

With the Gravitation[1] program, the Dutch Government aims to encourage research by consortia of top researchers in the Netherlands. Researchers must be carrying out innovative and influential research in their field. The program brings these experts together to enhance the international position of research in the Netherlands. The consortia belong to the world top in the field of research.

For the 2013 Call, the “Research Centre for Integrated Nanophotonics” was one of six consortia that were selected. It received a grant of 20 M€ for a period of 10 years. Five research groups from the Departments of Electrical Engineering and Physics (both Eindhoven University of Technology) cooperate in this program. The work started in January 2014 and this Report covers the first two years of research.

After some initial delay in finding and appointing qualified personnel the program is now making important steps in the realisation of its objectives. Major progress is being made in the application of photonic technologies in wireless access, through the use of steerable beams and in the backbone of the wireless network. Both will lead to significant energy savings in the access network. Major energy savings are also expected from the work on midboard optics for datacenters and from the photonic switching technology developed in the project.

In the field of integration technology major progress is reported in developing photonic components in thin InP-membranes on silicon, which can be used in highly efficient low-power photonic circuitry on top of CMOS electronics. Examples are an integrated nano light source, a very compact detector with record high bandwidth and a tuneable detector with record resolution.

In the field of materials and device research important progress has been made in studying ultra-fast modulation of lasers using optical signals instead of electrical signals. First steps have been made on the road to direct writing and reading magnetic memories with optical signals, which will eliminate the need for power-hungry o/e/o conversions. Finally, the technology for deposition of ultra-thin layers is developed for use in devices that operate close to the fundamental energy limits.

A number of joint activities have been started in the fields of improved passivation technology for nanolasers, advanced switching technology, integrated magneto-optic memories, novel epitaxial structures and PICs for radio-over-fibre networks.

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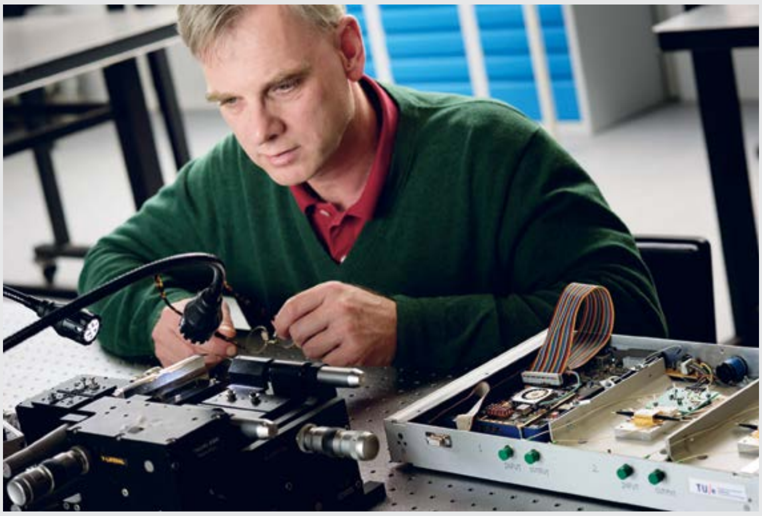
1 See http://www.nwo.nl/en/funding/our-funding-instruments/nwo/gravitation/gravitation.html

In Memoriam Prof.dr. Harm Dorren



In the early morning of Monday the 30th of March 2015, prof.dr. Harm Dorren, co-applicant of the Gravitation project *Centre for Integrated Nanophotonics* and scientific director of COBRA, suddenly passed away at the age of 49 years. He had just returned from a business trip to Los Angeles. On his return in Amsterdam, because of a serious infection, he underwent surgery urgently. Nevertheless he passed away shortly after.

Harm Dorren received his MSc degree in Theoretical Physics in 1991 and the PhD degree in Geophysics in 1995, both from Utrecht University, the Netherlands. He joined Eindhoven University of Technology in 1996 where he most recently served as a full professor and as the scientific director of COBRA – the Inter-University Research School on Communication Technologies Basic Research and Applications. COBRA is one of the world's top institutes in the field of optical communications. Between 1996 and 1999, he also was a part-time researcher in KPN-Research in the Netherlands. In 2002 he was a visiting researcher at the National Institute of Industrial Science and Technology (AIST) in Tsukuba in Japan. In 2013 and 2014 he was a visiting researcher at the Massachusetts Institute of Technology (MIT) in Boston, USA.

In 2002 he won an NWO VIDI award, and in 2006 an NWO VICI award. His research interests include optical (packet) switching, optical signal processing, ultrafast photonics and optical interconnects in data centres. With his entrepreneurial spirit, he also started a company on data centre technologies. Harm Dorren (co-)authored numerous papers in journals and conference proceedings and served as an associate editor of the IEEE Journal of Quantum Electronics between 2005 and 2009. As the scientific director of COBRA he was one of the key players in the photonics research. He was leading the photonics research for data centres, which is the leading theme for the present Gravitation project. His sudden decease is a great loss for his family, friends and colleagues, and also for the Centre for Integrated Nanophotonics.

Research objectives

Modern society depends on sustained increases in internet bandwidth, connectivity and computational power for business, entertainment, comfort, safety and communications. But the hardware at the heart of the internet consumes an unsustainable amount of energy and projections are showing a relentless increase. The energy consumption limits design and constrains connected bandwidth at every level of the network: inside computer systems, inside fibre-optic routers and at the final wireless connections to the user.

A radical new technology paradigm is required: we envisage a pervasive end-to-end optical connection between users and computing resources and a radical enhancement in electronic-to-optical conversion efficiencies. This requires the intimate integration of electronics and photonics at both the system level and at the physical layer and a re-engineering of photonics close to the quantum limit. It raises formidable scientific and technological challenges. We focus on the key hardware challenges in:

1.0 Pervasive optical systems

The creation of new integrated photonic circuits, which connect users optically to the network, which keep information in optical form as it passes through data routers in the internet backbone, and which handle unprecedented information densities as data streams converge at the servers at the heart of the internet.

2.0 Nanophotonic integrated circuits

The intimate integration of photonic circuits with electronic CMOS circuits using nanophotonic technology to push integration density and power efficiency several orders beyond today's state-of-the-art.

3.0 Ultimate control of light and matter

The ultimate control of light-matter interaction as we progress to the atomic scale, to ensure the ultimate in energy efficiency and information density. We will develop the tools to create and analyse optical nanomaterials optimized for efficient nanophotonic devices. We will also develop and study novel devices necessary for the efficient generation and detection of light at the femtojoule energy level. We study the exchanges of information between photons and magnetic spin as a route to fast and ultra-dense optically addressable memory.

The focus on new technology hardware offers a unique opportunity to proceed beyond the "proof-of-principle" and tackle both fundamental challenges and opportunities for large-scale applications. On the following pages we give a brief description of the research that we are doing to address the challenges described above, and of the most important results that we have achieved in the first two years of the project (2014 and 2015).

Work progress and achievements

1.0 Pervasive optical systems

Theme Coordinator: Ton Koonen

Highlights:

- World's first and most compact data centre switch with mid-board optics [*RAZ16*]
- World's largest InP monolithically integrated wavelength selector for optical packet routing [*STA14*, *STA15*]
- Record 42.5 Gbit/s downstream transmission through free-space pencil beam [*OHC15*]

1.1 Fibre wireless integration

Project leader: Ton Koonen

Significant power savings can be achieved in wireless communication by steering the signal in the direction of the user instead of sending it in all directions. We are investigating steering of optical beams, which have a potential for higher speed and lower power consumption. The concept of a 2D infrared optical pencil beam which can be steered by wavelength tuning using crossed diffraction gratings has been tested in a laboratory system. A record 42.5Gbit/s downstream transmission with 2.5 meter free-space reach has been demonstrated [*OHC15*]. Feasibility of the upstream transmission comprising recovery and remodulation of the downstream carrier and transport by radio-over-fibre techniques over an indoor fibre backbone link has been demonstrated [*KOO15*]. We have developed and demonstrated 2D beam steering with excellent performance by means of an integrated AWG-based true-time delay circuit [*CAO15*]. Further, we are exploring radio beam forming in a focal plane antenna array for satellite-to-home communication by means of tuneable integrated optical ring resonators. The feasibility has been shown by simulations and the required photonic integrated circuit has been designed.

Main objectives for 2016:

- Integration of 2D infrared pencil beam steering, with interleaved arrayed waveguide structures
- Integrated large angle-of-view optical receiver for infrared pencil-beam communication at >10Gbit/s
- Integrated ring resonator based true-time delay circuit for beam forming in focal plane antenna array system

1.2 Data centres and optical interconnects

Project leader: Oded Raz

The main system motivation for the use of compact and energy-efficient transceivers is to deploy them into data centre switches. In 2014 and 2015 a concentrated effort was made to create the world's first data centre switch using true mid-board optical modules. These are modules that generate optical signals close to the switching fabric and transport them from the switching board to the connectors, thus reducing the distance that has to be bridged by power-hungry electrical connections. The resulting system, which is now in production, measures only 200x200 mm and has a total bandwidth of 1.28Tbps. it will allow a 5X improvement in bandwidth density and 50% reduction in power consumption. By testing this system we will learn how to design the ultimate switch which will include the transceivers designed and fabricated in the project.

In order to make transceivers more compact 3D stacked transmitter and receiver arrays have been fabricated and demonstrated [*DUA13*, *DUA14*]. Testing of a 2.5D 12 channel 10 Gbps transmitter module has shown error free operation on all 12 channels. We are presently working on increasing the channel rate to 25 Gb/s, which will enable further enhancement of bandwidth density towards the 1 Tbps target.

Main objectives for 2016:

- Continue with the miniaturization of optical interconnects to the ultimate scale and develop novel integration schemes for them into data centre switches.
- Through further shrinking of interconnect modules, push the energy consumption further down towards the fundamental limit.
- Demonstrate the potential of optical interconnects in combination with tight system integration to improve the bandwidth density, packaging and power consumption of data centre networks by one order of magnitude

1.3 Optical Switching

Project leader: Kevin Williams

Optical switches hold the promise of seamless routing of high-speed data without the energy cost of electro-optic conversions. Data networks communicating with short packets of information require fast nanosecond speed switch actuation. As optical line rates scale with e.g. wavelength multiplexing, the need for optical domain processing increases further. While this can be achieved with efficient optoelectronic integrated photonic circuits, it is only recently that the scale of integration has been sufficient to start creating sufficiently high-connectivity switch matrices for low-latency, low-energy, high-capacity networking.

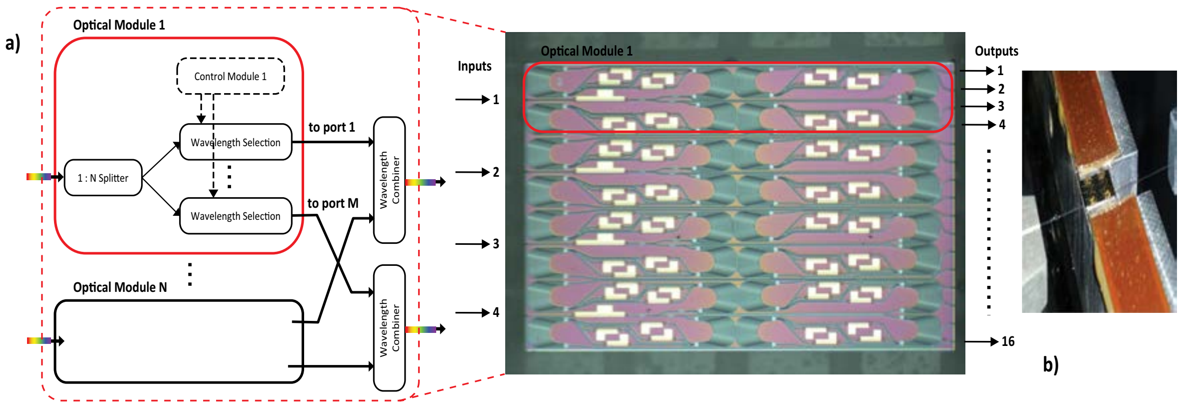


Figure 1
a) Schematic of the optical cross-connect. b) Photograph of the fabricated and wire bonded chip. (Illustration from [CAL15])

In the work of Calzadilla et al [*DOL14*], a method to create efficient and reliable optical coupling to membrane technologies was devised. While grating coupler techniques had been done before for Silicon on Insulator waveguides, the breakthrough here was to create a concept for InP optoelectronic circuits which was independent of the underlying layer. This is the critical step for creating optoelectronic circuits intimately wafer bonded to Silicon electronics.

Large scale switching matrices which are able to independently route arbitrary wavelength channels between arbitrary ports have been realised for the first time with an eight-port, packet-ready data switch. As a proof of principle experiment, sixteen data packets were routed through the switch within 16 μs. The data throughput was 160 Gb/s [*CHE15*, *CAL15*]. Methods to scale to a record number of 16 outputs have been demonstrated [*STA14*] along with techniques for real-time performance monitoring.

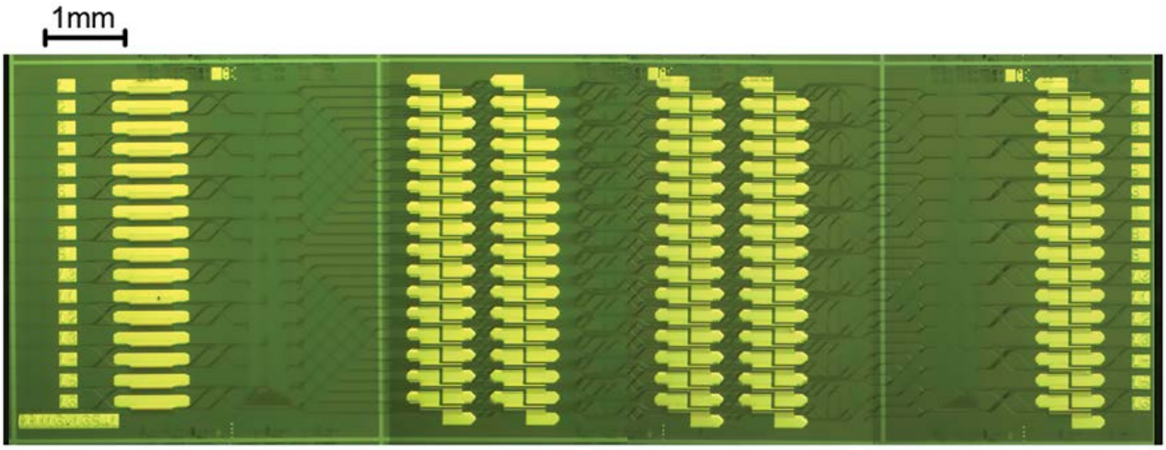


Figure 2
Fabricated 8 x 8 wavelength-and-space switch. (Illustration from [CHE15])

Main objectives for 2016:

- For future scaling, we will study 3D integration concepts for large scale integrated systems: monolithic multi-layer InP integration will be studied to enable a second plane of optical wiring.
- Resonant photonic devices will be studied to enable compact and energy efficient optical cross-point matrices. The use of higher order broadband resonant switches is expected to allow high line rate data.
- On-chip equalization will be studied for the first time in WDM based cross-connect circuits by extending in-line, on-chip monitoring for fast wavelength specific power adjustment.

Most important problems/deviations, impact on the planning and corrective actions
Due to the unexpected passing away of Prof. Harm Dorren, the principal applicant in charge of research towards innovation in data centres and optical interconnects, the program line on data centres is delayed. The lead in this research area has been taken over by Dr. Oded Raz, assistant professor in late Prof. Dorren's group.

2.0 Photonic integration

Theme coordinator: Meint Smit

Highlights:

- Waveguide-coupled nanoLED with record coupling efficiency into an integrated waveguide [*DOL16*]
- Tuneable micro-cavity detector with record wavelength resolution ~0.1 nm [*ZOB16*]
- First laser integrated in an InP nanophotonic waveguide platform on silicon [*JIA15*]
- Detector in InP-membrane with highest bandwidth for silicon-based devices (>67 GHz) [*SHE16*]

2.1 A high-density generic integration platform for photonic ICs on CMOS

Project leader: Meint Smit

Highly standardized generic integration processes offering a well-defined set of building blocks for realizing complex ICs were key to the success of microelectronics in the past decades. This enabled the use of one mass-manufacturable technology to support many product lines. In the last decade building blocks have been developed and introduced also for Photonic ICs. COBRA has played a leading role, and today these building blocks are finding their way to the market. In the present project we are working on a novel generation of generic integration technology, realised in a thin membrane for combining higher speed and smaller footprint with smaller energy consumption. This is additionally expected to enable close integration on top of (Bi)CMOS electronics. The most important building blocks for such a generic photonic integration platform are an optical amplifier, a high speed detector, a high speed modulator and a low-loss passive waveguide structure with which we can realize interconnections and a variety of passive components. We made progress on all four.

Optical amplifier: In cooperation with the PSN group we succeeded in demonstrating a first laser in our platform by integrating a membrane-based electrically driven optical amplifier with a passive ring resonator on a silicon substrate. *High-speed detector:* We succeeded in fabricating a membrane uni-travelling carrier (UTC) detector, with very good responsivity (0.7 A/W) and bandwidth: >67 GHz, the highest bandwidth reported for detectors on silicon substrates. In cooperation with the ECO group we demonstrated state-of-the-art system performance at 54 Gb/s and 5x40 Gb/s. *High speed modulator:* We are developing a process for integrating a so-called slot waveguide in our platform. By filling the slot with an electro-optic polymer we expect that this modulator can provide more than 40 GHz bandwidth. *Low-loss waveguide:* We have developed a process for etching low-loss passive membrane waveguides (photonic wires) with high resolution using ZEP-resist enforced with C60 (fullerene). Using this resist as a mask we have achieved waveguide losses as low as 2.5 dB/cm.

In 2015, two invited papers have been published on generic photonic integration and the pace of scale reduction. Moore's law is well established in the microelectronics industry and has reflected and driven the design and technology innovations for decades. In this important review [*SMI15*], Smit has been able to capture the sustained increases in photonic circuit complexity, and shown how membrane technologies and nanolasers fit seamlessly into an equivalent roadmap for photonics. In the case of photonics, the need for ever-simpler packaging solutions, intimate electronic connectivity, and lower energy needs drive the techniques being developed in this Gravitation research program.

The 2nd invited paper [*WIL15*] captures the adoption of generic technologies, technologies which are agnostic to application and have proven a key driver in the success of microelectronics. It shows how the building block concept can be extended to membrane devices. The techniques in hybrid and heterogeneous integration are key enablers, but additionally, advanced lithographic tools such as the deep UV scanner adapted for InP photonics and the innovative epitaxial designs for high confinement active membrane devices play a key role.

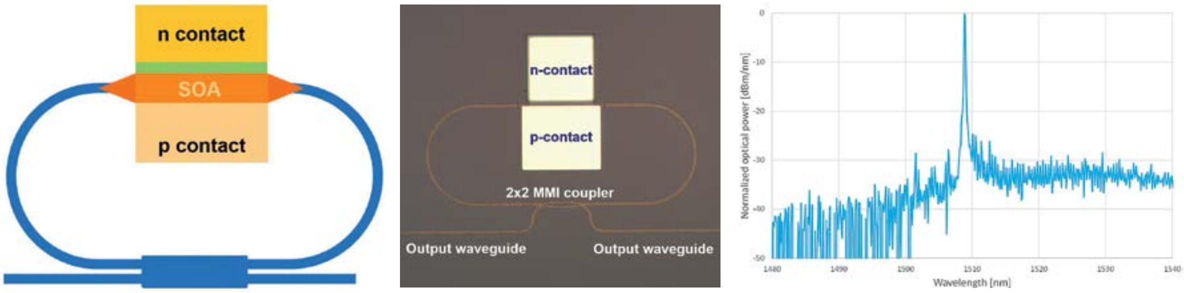


Figure 3
Schematic design of a ring laser on the IMOS platform. (b) microscope photograph of a fabricated ring laser with a 700 nm wide, 100 µm long amplifier. (c) Output spectrum of the laser.

Main objectives for 2016:

- Improvement of the efficiency of our membrane-based SOA to values comparable to discrete devices.
- Development of a process scheme for efficient integration of our high-speed detector and modulator with the optical amplifier.

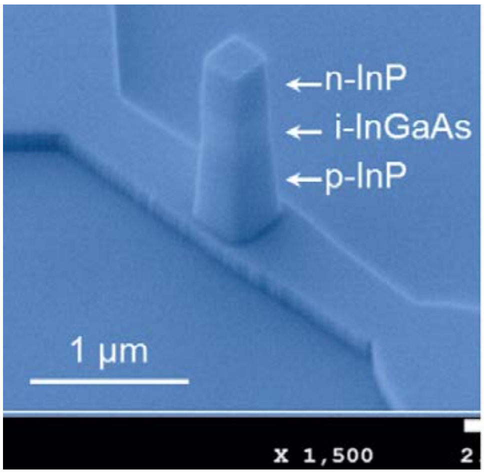
2.2 Ultralow-power components

Project leader: Andrea Fiore

We investigated novel, game-changing technologies that can reduce the footprint and power dissipation of active components by orders of magnitude, as needed in future high-density interconnects:

Nanoscale light sources
In a collaboration between PhI and PSN, the first waveguide-coupled nano-light-emitting diodes on a silicon substrate were demonstrated. They consist (Figure 4 left) of an InGaAs/InP nanopillar (~300 nm lateral dimension) surrounded by a dielectric (SiO_2) and metallic (Ag) shield, vertically-coupled to an IMOS waveguide. The measured light-current characteristics and the related modelling show that the nanoLED emits a large fraction of photons into the waveguide, resulting in a record efficiency value for waveguide-coupled nanoLEDs. Additionally, the first modulation experiments on nanoscale nanoLEDs were performed, showing a potential for data transmission at 1 Gb/s [*ZOB16*].

Nano-opto electro-mechanical systems
Electromechanical double-membrane photonic crystal (PhC) cavities (Figure 4 right) with record quality factor (Q > 15000) and tuning range (> 20 nm) have been demonstrated. Additionally, the integration of a p-i-n detector inside the electromechanical cavity has allowed us to demonstrate a tuneable photodetector with unprecedented wavelength resolution (~0.1 nm), which can be used as an ultra-compact integrated spectrometer/wavemeter. A novel technique of resonance modulation spectroscopy has been demonstrated with these structures, enabling resolutions in the pm range for the measurement of laser lines [*JIA15*]. Additionally, the first steps have been taken for the integration of nano-electromechanical structures on the IMOS platform in a collaboration between the PSN and PhI groups.



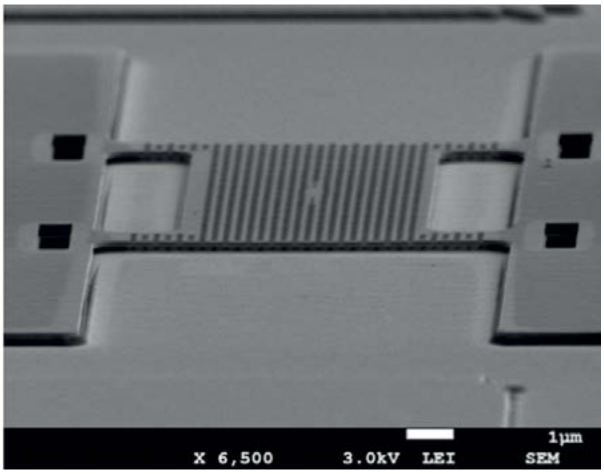


Figure 4
Left: SEM image of a waveguide-coupled nanoLED before Ag encapsulation. Right: SEM image of an electromechanical photonic crystal cavity.

Main objectives for 2016:

- Explore the potential of nanobeam Photonic Crystal lasers in an InP membrane on silicon as efficient compact light sources.
- Demonstrate an ultralow-power electromechanical phase shifter.

Most important problems/deviations, impact on the planning and corrective actions

The results presently obtained with metallo-dielectric nanoLEDs and nanolasers indicated that it will be difficult to get more than a few percent wall-plug efficiency with these devices. Simulations indicate that significantly better efficiencies can be achieved with nano-beam photonic crystal lasers. We started, therefore, research on nanobeam PhC lasers as an alternative to metallo-dielectric lasers for high-speed data interconnects.

3.0 Ultimate control of matter and photons

Theme coordinator: Paul Koenraad

Highlights:
- Ultrafast all-optical control of spontaneous emission in a photonic crystal cavity by changing the refractive index in an adjacent cavity [*JIN14*].
- Discovery of a new mechanism for applying a torque on ultrathin magnetic thin films by single femtosecond laser pulses that will allow further optimization of the efficiency of optical spin-transfer [*SCH14*].
- Successful conformal deposition of a range of thin film materials by atomic layer deposition (ALD) on nanowires of several types [*VOS16*].

3.1 Quantum effects in nanophotonic devices

Project leader: Andrea Fiore

In this project we investigate theoretically and experimentally novel components where quantum effects play a relevant role.

The first line of research on nanolasers has been the development of a rate equation model which allows describing in a physically-correct way cavity effects such as the Purcell emission enhancement. It is based on the treatment of spontaneous and stimulated emission on equal footing. This model will be critical for the modelling and design of the high-frequency modulation and feedback characteristics of nanolasers.

A second direction has been the theoretical and experimental investigation of nanocavities and nanolasers where an ultrafast modulation of the modal gain is obtained by modulating the vacuum field. In our first experimental demonstration [*JIN14*] we have introduced the concept of dynamic control of the vacuum field (and thereby spontaneous and stimulated emission) of an emitter in a cavity through the control of an adjacent cavity. More recently we have proposed a theoretical improvement of this scheme using three coupled cavities, allowing on/off field modulation without frequency chirp [*JOH15*]. We now aim at employing this effect for the gain modulation of a lasing nanophotonic cavity, which would result in the first demonstration of a new technique of "modal gain modulation" in a semiconductor laser.

Main objectives for 2016:
- Theoretical investigation of the modulation properties of metallo-dielectric and photonic crystal nanolasers
- Experimental demonstration of vacuum field switching in nanolasers

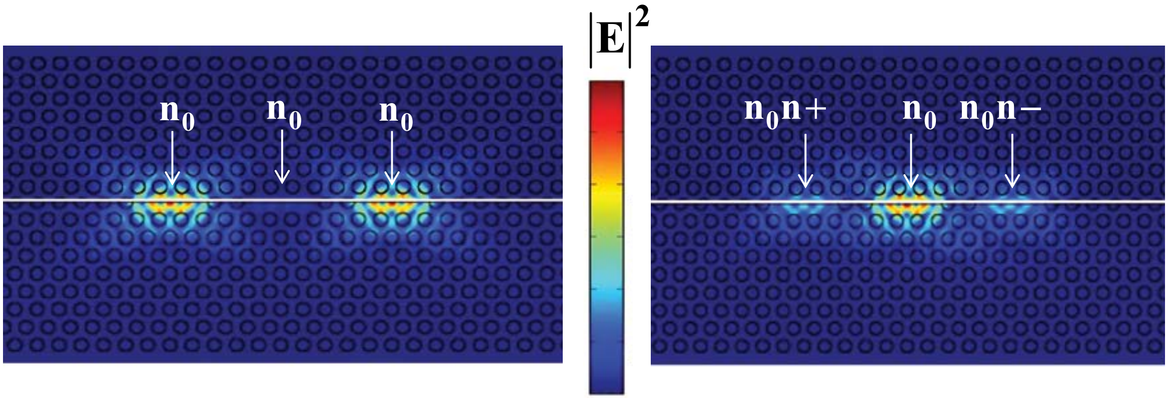


Figure 5
Calculated field distribution in a coupled three-cavity system in the cases where all cavities are resonant (left) and where the two lateral cavities are symmetrically detuned (right). The field modulation in the central cavity can be used to control the modal gain.

3.2 Hybrid approaches combining photonics and spintronics

Project leader: Bert Koopmans

Our research is focussed on creating spintronic memories that can be written directly with optical signals, thus avoiding the energy-wasting o/e/o conversions that are needed when using electronic memory. A new mechanism for applying a torque on ultrathin magnetic films by single femtosecond laser pulses has been reported [*SCH14*] and successfully characterized in more detail. Detailed studies on perpendicular/in-plane systems have been performed. Special focus was on varying spin-injection and absorption layers in order to increase fundamental understanding and thereby further optimize efficiency of the optical spin-transfer torque effects. In preparing for exploration of all-optical switching in synthetic ferrimagnetic systems, special magnetic thin film systems have been designed, prepared and their magnetic behaviour has been characterized.

A new amplified femtosecond laser system for exploration of all-optical switching has been purchased and set-up. The first time-resolved magneto-optical measurements on engineered magnetic thin films have been completed successfully.

Complementary to the all-optical studies, studies on magnetic-field and current-induced domain wall motion, exploiting the spin-Hall effect and DMI, have been performed [*CHO15*], preparing for integration with optical studies in the next phase of the project.

Main objectives for 2016:

- Completion of experimental infrastructure for all-optical and hybrid optical/electrical studies towards the photonic / spintronic memories
- Proof of principle demonstration of all-optical switching in racetrack medium
- Extend research towards current-induced movement of optically written magnetic domains
- First explorative studies of magneto-optical response of photonic waveguides with PMA (perpendicular magnetic anisotropy) ferromagnetic cladding.

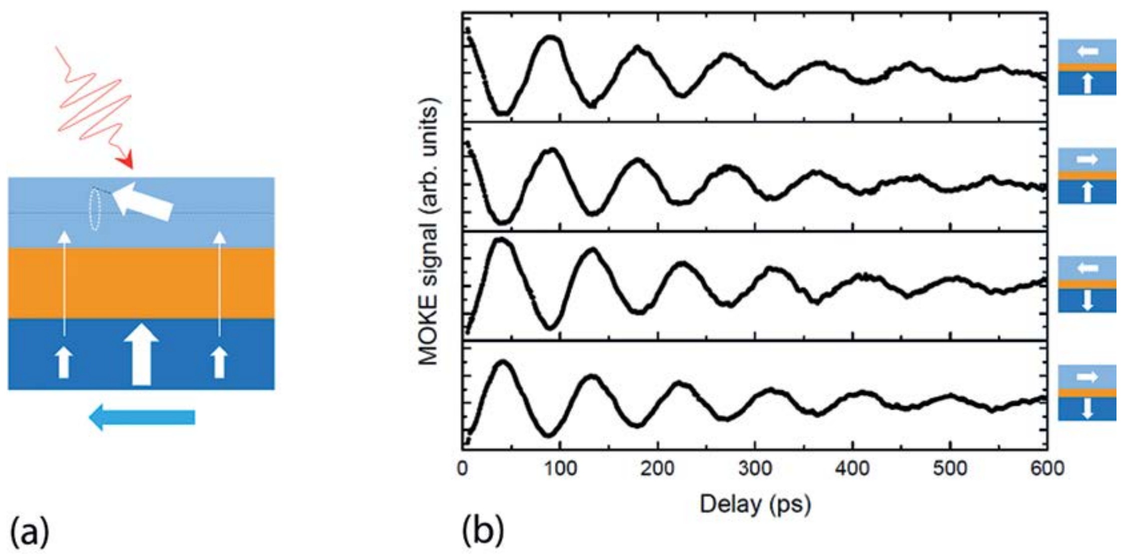


Figure 6
(a) Schematic representation of laser-induced spin torque, mediated by a spin current from the bottom magnetic nano-layer (fat arrow represents magnetization) to the top magnetic layer. (b) Time resolved magneto-optical measurement of the induced magnetization precession, reversing its polarity upon reversal of the magnetization of the bottom layer.

3.3 Nanomanufacturing for photonics

Project leader: Erwin Kessels

It is the aim of the nanomanufacturing program to provide solutions and opportunities for the other research activities of the project, in particular for photonic integration research, by pioneering new methods to provide a nanotechnology toolbox while conducting science at the highest level. In the recent period, particular attention has been paid on advancing atomic layer processing techniques, including (area-selective) atomic layer deposition (ALD) and atomic layer etching (ALEt) [*MAK14*, *FAR15*].

The application of ALD to deposit ultrathin films on semiconductor nanowires has been investigated in close cooperation with the PSN group. Various types of nanowires (Si, Ge, GaP, InP) prepared by vapor-liquid-solid (VLS) growth have been covered with a range of thin film materials (Al_2O_3, TiO_2, ZnO, In_2O_3) using existing ALD processes [*VOS16*]. Furthermore, a novel ALD process for HfO_2 has been developed over relatively large temperature range, i.e. from 150 to 400 °C [*LON16*]. For the nanowires, the film growth as well as the interfacial properties have been investigated by advanced transmission-electron-microscopy (TEM) studies. Aspects such as film conformality and nucleation effects have been mapped. We expect that our improved insight into the opportunities of ALD for nanowire devices in terms of protection, passivation and functionalization of the nanowires will prove important in the next phase of the project.

In cooperation with PSN and PhI a study to improve the passivation of nanowires and nanopillars has been initialized. The aim is to reduce the surface recombination of the charge carriers in the nanowires and nanopillars by decreasing the density of recombination sites at the surface through the application of atomic-layer-deposited thin films such as Al_2O_3. High quality passivation is very important for realizing both energy efficient nanolasers and solar cells.

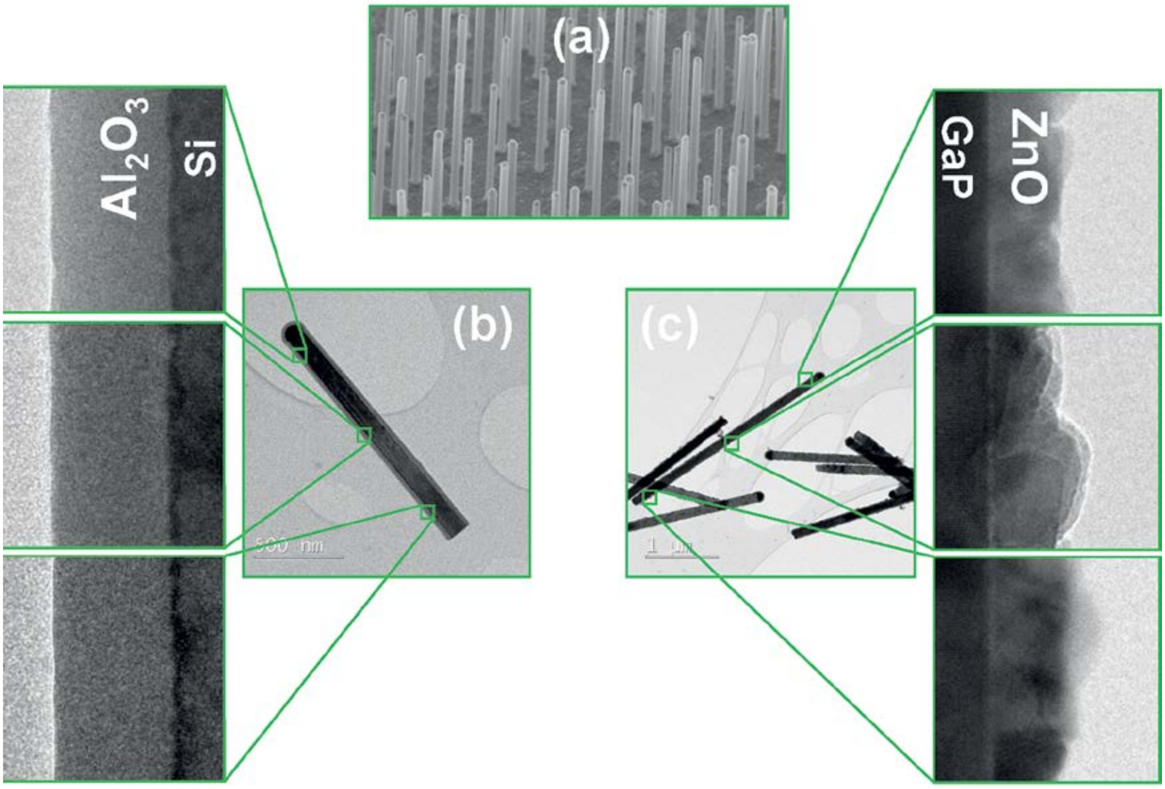


Figure 7
(a) Scanning electron microscopy image of a GaP nanowire array. (b) Transmission electron microscopy images of (b) a conformal Al2O3 film prepared by plasma ALD on a Si nanowire and (c) a polycrystalline ZnO film prepared by thermal ALD on a GaP nanowire.

Main objectives for 2016:

- Extending the capabilities to cover nanowires by conformal thin films prepared by atomic layer deposition (ALD).
- Improving and understanding the surface passivation of semiconductor nanowires and nanopillars by atomic-layer-deposited films.
- Extending and advancing the capabilities of preparing ultrathin films and 2D materials that are of interest within the research program on nanophotonics.

Most important problems/deviations, impact on the planning and corrective actions

There are no significant problems or deviations from the planned activities.

Publications and joint research

The research carried out in the Gravitation Project builds on current research of the participating groups. In 2014 and 2015 they published 131 and 143 papers, respectively, on topics related to the Gravitation project, of which 34 were joint papers.

In the framework of the Gravitation project a number of novel activities has been started. The table below lists the publications of the project which are referenced in the report.

Examples of novel joint activities that have been started are the research into improved passivation technology for nanolasers (PSN, PhI, PMP), research on advanced switching technology (ECO, PhI), research on integrated magneto-optic memories (FNA, PhI), research on novel epitaxial structures (PhI, PSN), and research on PICs for radio-over-fibre networks (ECO, PhI).

List of referenced publications

	Publication	Group
CAL15	Calabretta N., Dorren H. & Williams K.A. (2015). *"Monolithically integrated WDM cross-connect switch for nanoseconds wavelength, space, and time switching"*. 2015 European Conference on Optical Communication (ECOC), 27 September - 1 October 2015, Valencia, Spain (pp. 1-3). Piscataway: IEEE (2015).	ECO
CAO15	Cao Z. (2015). *"Radio beam steering in indoor fibre-wireless networks Eindhoven"*. PhD thesis Technische Universiteit 2015 (PhD Degree awarded Cum Laude).	ECO
CHE15	Cheng Q., Stabile R., Rohit A., Wonfor A., Penty R.V., White I.H. and Williams K.A. (2015). *"First demonstration of automated control and assessment of a dynamically reconfigured monolithic 8x8 wavelength-and-space switch"*. Journal of Optical Communications and Networking, 7(3), A388-A395.	ECO
CHO15	Cho J., Kim N.-H., Lee S., Kim J.-S., Lavrijsen R., Solignac A., Yin Y., Han D.-S., Van Hoof N.J.J., Swagten H.J.M., Koopmans B. and You C.-Y. (2015). *"Thickness dependence of the interfacial Dzyaloshinskii–Moriya interaction in inversion symmetry broken systems"*. Nature Communications 6, 7635, http://dx.doi.org/10.1038/ncomms8635.	FNA
DOL14	Dolores Calzadilla V. M., Heiss D. & Smit M. K. (2014). *"Highly efficient metal grating coupler for membrane-based integrated photonics"*. Optics Letters, 39(9), 2786-2789. 10.1364/OL.39.002786	PHI
DOL16	Dolores-Calzadilla V., Romeira B., Pagliano F., Birindelli S., Higuera-Rodriguez A., Van Veldhoven P.J., Smit M. K., Fiore A. and Heiss D. (to be published 2016). *"Waveguide-coupled nanopillar metal-cavity light-emitting-diodes on silicon"*.	PHI
DUA13	Duan P. et al (2013). *"Demonstration of Wafer Scale Fabrication of 3D Stacked Transmitter and Receiver Modules for Optical interconnects"*. Journal of Lightwave Technology, vol. 31, no. 24.	ECO
DUA14	Duan P. (2014). *"A novel 3D stacking approach for chip-to-chip interconnects Eindhoven"*, PhD thesis Technische Universiteit Eindhoven 10.6100/IR781403	ECO

FAR15	Faraz T., Roozeboom F., Knoops H. C. M., & Kessels W. M. M. (2015). "*Atomic layer etching : what can we learn from atomic layer deposition?*" ECS Journal of Solid State Science and Technology, 4(6), NS-023/032. 10.1149/2.0051506jss.	PMP
JIA15	Jiao Y., Heiss D., Shen L., Bhat S., Smit M. and Van der Tol J. (2015). *"First Demonstration of an Electrically Pumped Laser in the InP Membrane on Silicon Platform"*. IPR 2015, paper IM4B.3.	PHI
JIN14	Jin C.Y., Johne R., Swinkels M.Y., Hoang T.B., Midolo L., Van Veldhoven P.J. and Fiore A. (2014). *"Ultrafast non-local control of spontaneous emission"*. Nature Nanotechnology Letters, 14 Sep 2014.	PSN
JOH15	Johne R., Schutjens R., Fattah Poor S., Jin C.Y., and Fiore A. (2015). *"Control of the electromagnetic environment of a quantum emitter by shaping the vacuum field in a coupled-cavity system"*. Phys. Rev. A 91, 063807.	PSN
KOO15	Koonen A.M.J., Oh C.W., Mekonnen K., Cao Z. and Tangdiongga E. (2015). *"Ultra-High Capacity Indoor Optical Wireless Communication Using 2D-Steered Pencil Beams"*. Proc. of Microwave Photonics Conference 2015, Paphos, Cyprus, Oct. 2015, and accepted for publication in IEEE J. of Lightwave Technology, to be published 2016.	ECO
LON16	Longo, V., Sharma, A., Bol, A.A. and Kessels, W.M.M. (to be published 2016).	PMP
MAK14	Mackus A. J. M., Bol A. A., & Kessels W. M. M. (2014). "*The use of atomic layer deposition in advanced nanopattering.*" Nanoscale, 6(19), 10941-10960. 10.1039/C4NR01954G, 10.1039/c4nr01954g.	PMP
OHC15	Oh C.W., Tangdiongga E. and Koonen A.M.J. (2015). *"42.8 Gbit/s indoor optical wireless communication with 2-dimensional optical beamsteering"*. Presented at the Opt. Fiber Commun. Conf. Exhib., Los Angeles, CA, USA, Mar. 2015, Paper M2F.3.	ECO
RAZ16	Raz O. et al (2016). *"Optical Solutions for the Challenges of Mega-Size Data Center Networks"*. Invited talk at OFC 2016, W1J.4, 2016.	ECO
SCH14	Schellekens A. J., Kuiper K. C., De Wit R.R.J.C. and Koopmans B. (2014). *"Ultrafast spin-transfer torque driven by femtosecond pulsed-laser excitation"*. Nature Communications 5, 4333. http://dx.doi.org/10.1038/ncomms5333.	FNA
SHE16	Shen L., Jiao Y., Yao W., Cao Z., Van Engelen J.P., Roelkens G., Smit M.K. and Van der Tol J.J.G.M. (to be published 2016). *"High-bandwidth uni-traveling carrier waveguide photodetector on an InP-membrane-on-silicon platform"*. Accepted for publication in Optics Express.	PHI
SMI15	Smit, M. K. (2015). De wet van Moore voor fotonica. Nederlands Tijdschrift voor Natuurkunde, 81(4), 78-81.	PHI
STA14	Stabile R., Rohit A. and Williams K.A. (2014). *"Monolithically integrated 8x8 space and wavelength selective cross-connect"*. Journal of Lightwave Technology, 32(2), 201-207.	ECO
STA15	Stabile R., Calabretta N., Williams K.A. & Dorren H.J.S. (2015). *"Monolithic 16-wavelength selector based on a chain of passband-flattened cyclic AWGs and optical switches"*. Optics Letters, 40(8), 1795-1797. 10.1364/OL.40.001795.	ECO
VOS16	Vos V.M., Black L., Verheijen M.A., Bol A.A., Kessels W.M.M. (to be published 2016)	PMP
WIL15	Williams, K. A., Bente, E. A. J. M., Heiss, D., Jiao, Y., Lawniczuk, K., Leijtens, X. J. M., ... Smit, M. K. (2015). InP photonic circuits using generic integration. Photonics Research, 3(5), B60-B68. 10.1364/PRJ.3.000B60.	PHI
ZOB16	Zobenica Ž., Van der Heijden R.W., Petruzzella M., Pagliano F., Leijssen R., Xia T., Midolo L., Cotrufo M., Cho Y.-J., Van Otten F.W.M., Verhagen E., Fiore A. (tob e published 2016).	PSN

Budget and personnel

Summary

For the Gravitation program the filling of available positions shows some delay as compared to the planning, but is steeply increasing. As a result, also investments in equipment as cleanroom use are lagging behind. The main reason for the delay are difficulties in attracting qualified personnel and PhD students, and another reason has been the unexpected passing away of prof. Dorren which has delayed part of the core program. Figure 8 shows that, where the number of people appointed on the project in 2014 and 2015 was significantly less than planned, we expect to reach the expected effort level in 2016. In 2017 we expect to exceed the planned effort level in order to catch up for the delays in the first two years.

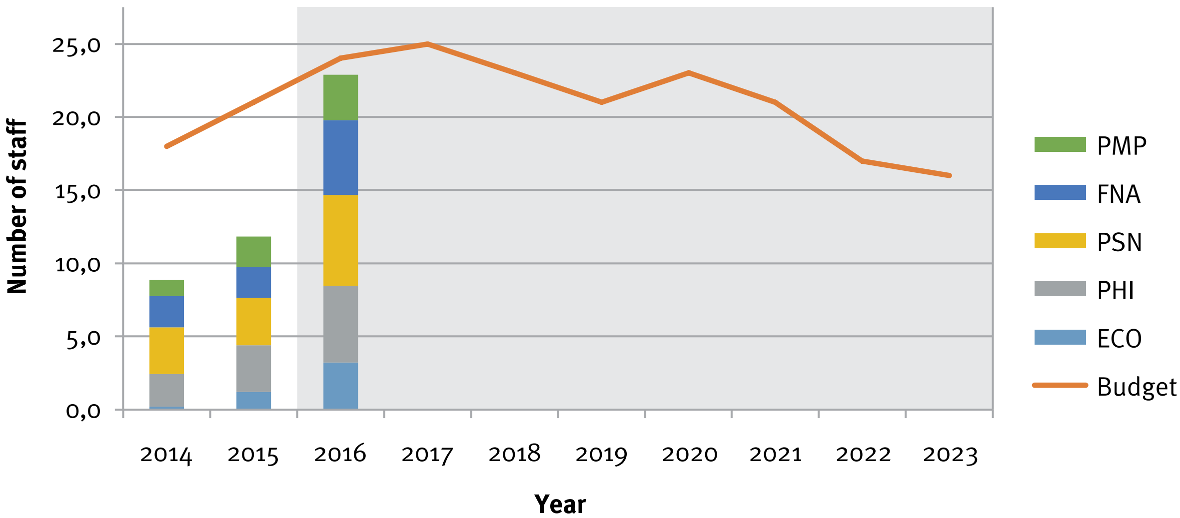


Figure 8
Personnel budget and appointed

Figure 9 (next page) show the difference between the cumulative budget and the cumulative spending and commitments so far. Blue bars on a grey background indicate reservations for currently hired personnel. Yellow bars indicate the commitments which are planned for 2017 and following years.
In conclusion, the project is well underway after a slow start in 2014 and 2015.

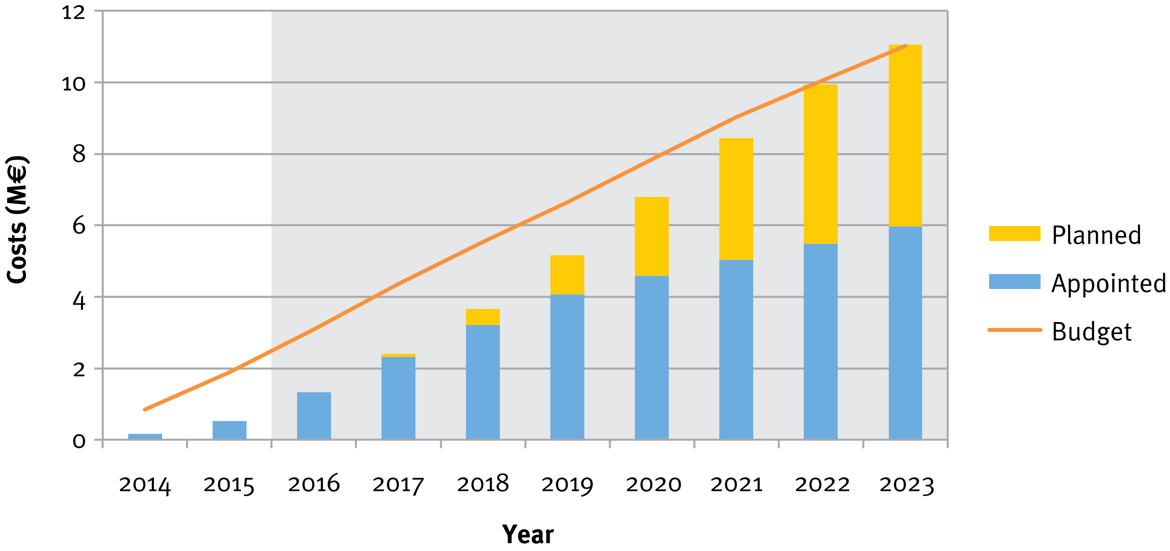


Figure 9
Cumulative personnel budget and costs

Institutional embedding and organisational structure

Organisational and Management Structure

The project is managed by a management team consisting of the chairmen of the five groups participating in the project, a scientific director, a managing director and a scientific secretary.

Scientific Director: Prof. Meint Smit (Chairman)
Managing Director: Prof. Ton Backx
Secretary: Dr.ir. Jan Vleeshouwers
Members:
Prof. Ton Koonen (chairman Optical Communication Systems group ECO, Electrical Engineering)
Prof. Kevin Williams (chairman Photonic Integration group PhI, Electrical Engineering)
Prof. Paul Koenraad (chairman Photonics and Semiconductor Nanophysics group PSN, Applied Physics)
Prof. Bert Koopmans (chairman, Physics of Nanostructure group FNA, Applied Physics)
Prof. Erwin Kessels (chairman, Plasma Materials and Processing group PMP, Applied Physics)

The management team meets every month to discuss project progress and management issues. The team is a subset of the COBRA Management Team and meetings are organized in conjunction with the COBRA MT Meetings. Dr.ir. Jan Vleeshouwers is secretary of both COBRA and the present Gravitation Project. Financial and HR-support is provided by TU/e (Ton Derkx and Wilma van Eck respectively).

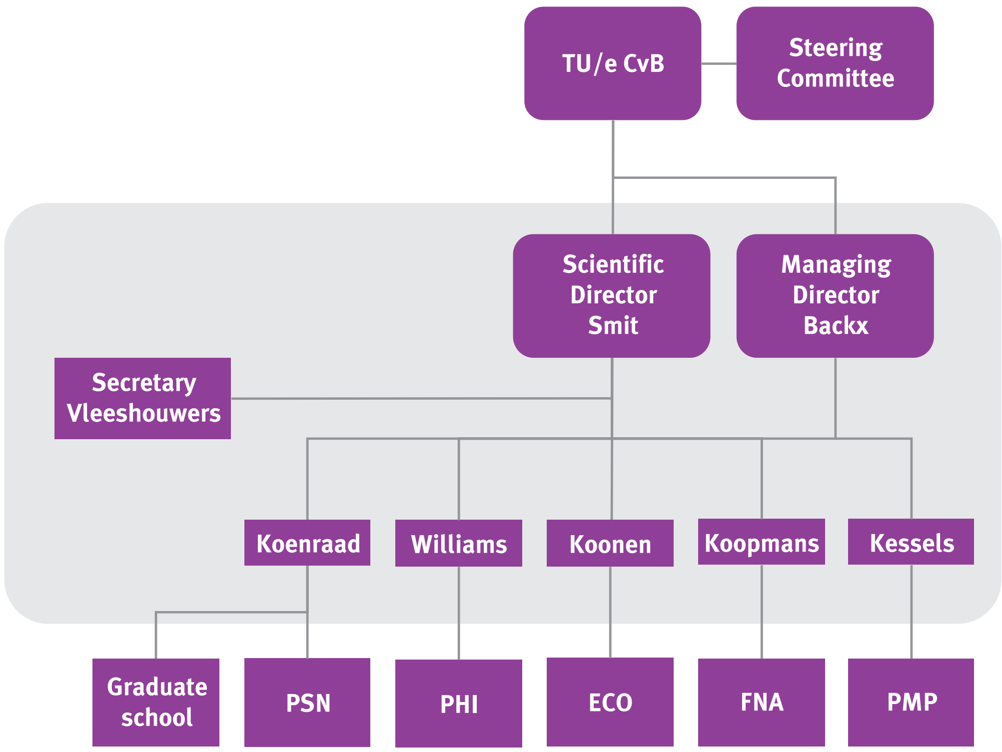


Figure 10
Management Structure of the Research Centre for Integrated Nanophotonics

Steering Committee

A Steering Committee, composed of seven members, oversees the overall research strategy and progress of the Research Centre, approves the yearly report and advises the management team about the research program.

The Steering Committee consists of the following members:
Chairman: Prof. Frank Baaijens, Rector of the TU/e
Secretary: Dr. ir. Jan Vleeshouwers, TU/e
Members:
Prof. Rod Alferness, Dean of the College of Engineering, University of California Santa Barbara (UCSB)
Prof. Henning Riechert, Director Paul Drude Institut, Berlin
Prof. Sailing He, Director Sino-Swedish Joint Research Center Photonics (JORCEP), ZheJiang University
Prof. Jos Benschop, senior vice president ASML
Prof. Bart Smolders, Dean of the TU/e Faculty of Electrical Engineering
Prof. Gerrit Kroesen, Dean of the TU/e Faculty of Applied Physics

Organisational Embedding and Cooperation

The Gravitation project *Centre for Integrated Nanophotonics* is embedded in the COBRA Research Institute, which employs about 200 persons, 40 of which are involved in the Gravition project. It is the largest project of COBRA. Through COBRA and Nanolab@TU/e, which is one of the world's most advanced university cleanroom facilities for Photonic Integration, it has access to world-class facilities for design, fabrication and characterization of photonic materials, devices, circuits and systems. The Research Centre benefits from the broad national, European and international network of the COBRA Research Institute, both in the academic and the industrial world.
Photonics is one of the central research themes of the Eindhoven University of Technology, which has been strongly investing in this field for more than two decades. Photonics has recently been recognized as one of thirteen major areas in the national top sector High-Tech Systems and Materials (HTSM) in which Universities are cooperating with the high-tech industry.

Educating and attracting talent

Photonics has an increasing presence in the TU/e education curriculum, through a new Bachelor College course, a special Master program in *Broadband Telecommunication Technology* and the recently established *NWO Graduate school on Photonics*, which offers a training program for PhD students and Master students in Photonics. An additional special master track is being prepared in *Photronics: integration of Electronics and Photonics"*. This initiative will be key for the development of the field, because all photonic integrated circuits require electronic drivers, receivers, controllers and processing circuitry. The new Master track will provide the necessary training program for electronic-photonic co-design.
In a general context of a shortage of qualified personnel, the institute is successful in attracting highly qualified researchers and excellent PhD students, due to the international reputation of the COBRA institute and its excellent cleanroom facilities. The Gravitation project offers significant means to strengthen the scientific quality of the COBRA staff and students. The PhI group is presently advertising a new full-professor position funded from the Gravitation budget. Both the FNA group and the PMP group have appointed highly qualified assistant professors. Further 8 PhD students have started research on the Gravitation project.

Knowledge utilisation

The COBRA research institute, in which the Gravitation project is embedded, has an excellent track record in cooperation with industry and turning scientific research achievements into industrial applications. In the last five years COBRA students and researchers have started five spinoff companies: SMART Photonics, EFFECT Photonics, PhotonX, Bright Photonics and NanoPhab. COBRA PhD students are closely involved in a number of other companies active in the field.
COBRA is leading the Joint European Project for Photonic Integration of Components and Circuits, JePPIX[2], in which Europe's key players in Photonic Integration are cooperating in setting up the technological infrastructure for making advanced photonic integration processes accessible to SMEs and larger companies through low-cost access via so-called Multi-Project Wafer (MPW) runs. JePPIX is the world's first and only organisation that provides commercial MPW access to advanced InP-based generic integration processes. JePPIX offers an excellent platform for transferring novel technology developed in the Gravitation project into industrial applications.
TU/e is presently setting up a business accelerator organisation, called Photon Delta, with companies from the Eindhoven region and beyond, in order to accelerate the commercialisation of the research achievements of the COBRA groups.

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[2] JePPIX partners are three PIC-manufacturers: Oclaro Technology (UK), Fraunhofer HHI (DE) and SMART Photonics NL; three Photonic CAD companies: PhoeniX Software (NL), Photon Design (UK) and Filarete (IT); a Packaging Company: Linkra (IT); two Photonic Design Houses: VLC Photonics (ES) and Bright Photonics (NL); and four research organisations: III-V Lab (FR), Cambridge University (UK), Politecnico de Milano (IT) and COBRA. COBRA is leading JePPIX. See http://www.jeppix.eu/.