# Research Centre for Integrated Nanophotonics

## ANNUAL REPORT 2019

**1 JUNE 2020**

Institute for Photonic Integration

Materials • Devices • Systems

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# FACTS

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(as of 1 June 2020)

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# EXECUTIVE SUMMARY

The Gravitation program has completed its sixth year, a year rich of scientific results and new initiatives for internal networking, valorization, outreach.

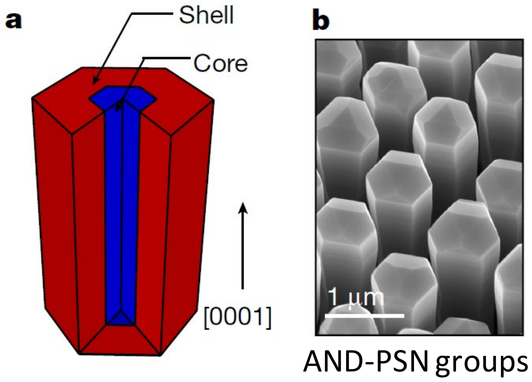
On the scientific side, Theme 1 has witnessed continuous progress in wireless optical communication, in particular with a demonstration of non-line-of-sight optical wireless transmission. Our new research line on optical neural networks has also reached an important result, namely a lossless, monolithically integrated photonic neuron, while work on spatial division multiplexing has focussed on improving the analysis instrumentation. In Theme 2 we have seen continuous progress on the IMOS platform, with substantial improvements in optical losses, quality of gratings and passive devices, and the integration of polymeric electro-optic modulators. Most significantly, the new integration platform is now being investigated for sensing applications in nanometrology and spectroscopy – areas not originally foreseen in the program and with a near-term application potential. Within theme 3 one of the most ambitious activities, the development of new Si-based light emitters using crystal structure engineering, has brought a major success – the demonstration of SiGe nanowires with radiative properties comparable to traditional III-V heterostructures. Other research lines related to new materials or novel effects, such as atomic-layer deposition of 2D semiconductors, all-optical switching of magnetic domains for optical memories, and exciton-polariton lasing, are bringing a wealth of new results.

In 2019 the program had its first annual retreat (1.5 days), which was a major scientific and social event for the Eindhoven photonics community. A program aimed at involving more Master students in the program activities, the *"PhotonDelta Fast Career Track Program"*, and a student chapter *"Photonics Society Eindhoven"* were both started in 2019 and are already contributing to the creation of a network of students and companies. In an effort to identify and realize potential impact, a first version of the utilisation strategy has been drafted: Potential areas have been identified (as described in this report), programs for technology development at higher TRL levels have been defined for funding by PhotonDelta and *"Application Bootcamps"* have been organized together with PhotonDelta. Initiatives for stimulating and supporting photonics start-ups are under discussion for 2020. A second spin-off related to photonics – TeraNova - was launched within the consortium and more initiatives are being discussed. Finally, the program had its first substantial outreach activity, with a strong participation to the *Dutch Design Week* (8 photonics demonstrations and related presentations within the TU/e exhibit, 17'000 visitors).

The program and its participants are also getting increasing attention in the scientific community and in the media: Erik Bakkers gave a plenary talk on direct-gap SiGe nanowire at Photonics West, Ton Backx participated to a prime-time documentary on data centers on the Dutch TV, Bert Koopmans and Erwin Kessels had honorary appointments, and the TU/e honorary doctorate 2019 was awarded to Dr. Peter Winzer for his work on optical communication systems.

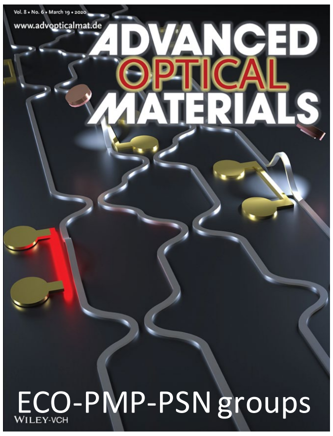
# GRAVITATION HIGHLIGHTS IN IMAGES

Direct bandgap SiGe nanowires
*Nature 2020*

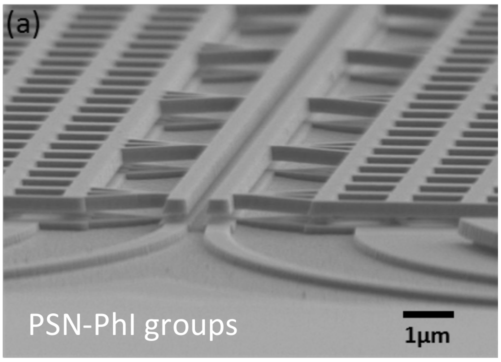



AND-PSN groups

Reconfigurable integrated photonics
*Advanced Optical Materials 2020*



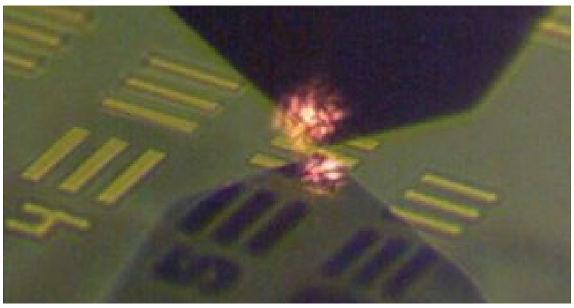

ECO-PMP-PSN groups




PSN-PhI groups

Nanomechanical sensors on the IMOS platform
*Nature Communications 2020*

Integrated Photonics on show at the Dutch Design Week 2019



TeraNova

A joint physics/EE spin-off

# OVERVIEW OF THE 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 fiber-optic routers and at the final wireless connections to the user.

In order to solve these outstanding issues, 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 on all scale levels.

### THEME 1 PERVASIVE OPTICAL SYSTEMS

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

The systems must help solve the capacity bottleneck at every network level from the long-haul transmission systems through data-center networks and including down to access networks and in-home networks, where billions of users need fast connections with the local and global internet.

The Gravitation research targets different parts of the communication infrastructure:

- Long haul transmission of data, where photonic integration techniques will be exploited to open new dimensions and increase the amount of data that can be transported over a single fiber.
- Signal routing and processing, where applications of adding versatile photonic circuits to electronic circuitry are being investigated as well as the introduction of optical switches for energy-efficient and transparent switching and routing of data.
- Closer to the user, the research is aimed at photonic chips as a means to create dynamically reconfigurable indoor access points, a low-cost indoor optical network, and beam-steering techniques for short-range wide-band low-power radio- and optical-wireless connections.

### THEME 2 NANOPHOTONIC INTEGRATED CIRCUITS

We aim to intimately integrate active photonic circuits with electronic silicon-based circuits using nanophotonic technology to push integration density and power efficiency several orders beyond today's state-of-the-art.

The research line has two parts:

- Creation of a nanophotonic membrane based integration platform that supports integration of compact and energy efficient basic building blocks used in photonic circuits for a variety of applications. These membrane-based photonic circuits are created on top of silicon or CMOS integrated circuits, which contain the electronics for driving and controlling the optical circuits and for processing the electronic data that they generate.
- Creation of compact and ultra-low power components for future integration in the platform. Emphasis is on nanolasers and photonic switches.

### THEME 3 ULTIMATE CONTROL OF LIGHT AND MATTER

We aim at ultimate control of light-matter interaction on an atomic scale, to ensure the ultimate in energy efficiency and information density, and to explore ways of manufacturing. The emphasis is on tools to create and analyze optical nanomaterials for efficient nanophotonic devices and to develop and study novel devices for efficient generation and detection of light at the femtojoule (fJ) energy level. We also study the exchange of information between photons and magnetic spin as a route to fast and ultra-dense optically addressable memory.

We are investigating techniques for creating and manipulating structures on the nanoscale, which display properties which are not found in natural materials. One example is the growth of hexagonal Si and SiGe nanowires, the first samples of which show the expected direct bandgap. This novel material may enable efficient emission from silicon, or the monolithic integration of materials with different crystal structure or lattice constant (e.g. III-V on Si or vice versa). This work is made possible by the use of atomic-scale characterization techniques which identify these structures atom-by-atom. Another research line investigates processes where light directly interacts with magnetic properties of matter, which opens ways for optical memories. These are still a major target in the design of optical circuits. Major challenges are encountered and addressed in both the scientific analysis and the manufacturing methods.

### ORGANIZATION

All staff members involved in the Gravitation Program “Research Centre for Integrated Nanophotonics” belong to the TU/e Institute of Photonic Integration (IPI). This institute provides the input to a pipeline which brings research to application (see the section on Institutional Embedding).

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 sixth year of the project (2019).

In some cases, activities in the Nanophotonic Gravitation program have led to spin-off research activities: see the section on Knowledge Utilization.

# WORK PROGRESS AND ACHIEVEMENTS

## THEME 1 PERVASIVE OPTICAL SYSTEMS

*Theme Coordinator: Ton Koonen*

**Highlights:**

- Non-line-of-sight optical wireless transmission of 30Gbit/s data [CAO19]
- Lossless Monolithically Integrated Photonic InP Neuron for All-Optical Computation [SHI20]
- Metastable Refractive Index Manipulation in Hydrogenated Amorphous Silicon for Reconfigurable Photonics [RAZ20].
- Best paper award at OECC/PSC2019 conference on optoelectronics and communication in Fukuoka (Japan) [HEI19].

### THEME 1.1 **Fiber wireless integration**

*Project leader: Ton Koonen*

#### OPTICAL WIRELESS COMMUNICATION

In the ERC Proof-of-Concept project BROWSE+, in expanding our demonstrator system for ultra-high capacity wireless communication by means of 2D-steered infrared narrow optical beams, we have introduced a novel user device localization technique which requires only a passive functionality at the user side [KOO19]. We deployed commonly available foil-embedded arrays of miniature corner cube reflectors, and demonstrated device localization well within the required accuracy (the femtocell size of the optical beam's footprint, ca. 10cm). By driving the wavelength-controlled beam steering using this self-calibrating localization technique, autonomic establishment of the optical link connection to the user was demonstrated. We showed its feasibility in our laboratory system demonstrator (see Figure 1). Within the SMART-One project in cooperation with KPN, as an alternative approach for localization we explored camera observation of active LED tags at the user device, and we achieved a localization accuracy within 5mm [PHA19].

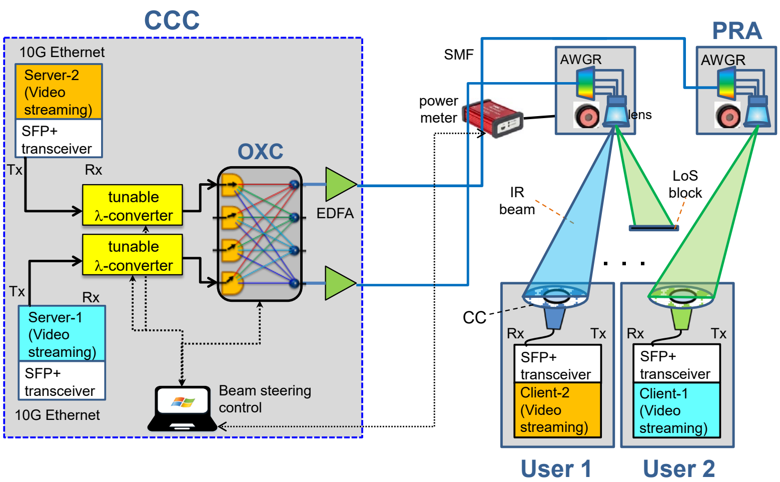



*Figure 1 Optical wireless communication laboratory system demonstrator featuring passive user device localization and path diversity for circumvention of line-of-sight blocking.*

In order to mitigate line-of-sight (LoS) blocking and to extend the coverage area, we expanded the setup with another pencil beam radiating antenna (PRA) module and introduced path diversity by introducing a MEMS optical crossconnect switch for the connection routing. We demonstrated the robustness against LoS blocking in our laboratory setup featuring high-definition video transfer embedded in 10Gbit Ethernet streams to two users independently [KOO19a]. For further extending the coverage area of the AWGR-based PRA, we also have investigated the use of orthogonal polarization states in order to double the number of beams [ZHA19a].

At the user device side, the challenge is to create a free-space optical receiver with both large aperture and large angular Field-of-View, and also with a large bandwidth in order to support a high data rate. Within the limits of the physics law of conservation of etendue, we designed a novel photodetector architecture stretching these limits as well as yielding a large receiver bandwidth. Its technical validation has started. This novel concept has been filed as US Provisional Patent [KOO19b].

Alternatively, we have investigated the mitigation of LoS blocking by using reflections from diffuse surfaces and adaptive wavefront shaping by means of a spatial light modulator (SLM) in order to circumvent obstacles [CAO19]. We showed basic feasibility by transmission of a 30Gbit/s OFDM signal over a sub-meter indoor diffuse link (Figure 2).

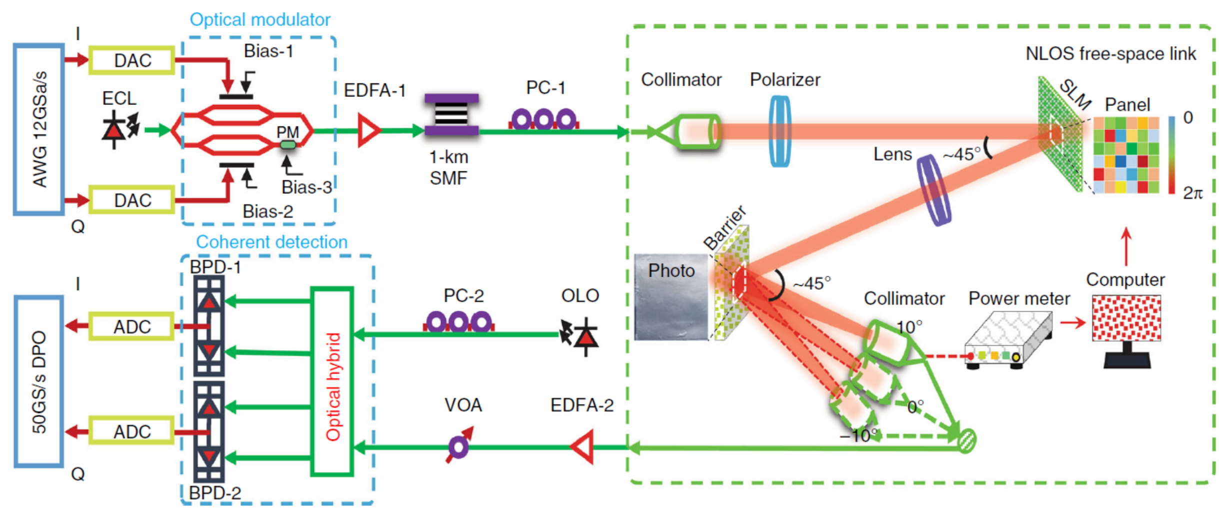



*Figure 2 Non-line-of-sight optical wireless communication by exploitiung diffuse reflection and wavefront shaping*

In the H2020 ELIOT project, which addresses optical wireless communication (OWC) for Internet-of-Things applications, we are investigating novel feeder link technologies for the foreseen LED luminaires. We explore POF (plastic optical fiber) technology with wavelength-multiplexed multi-channel transport in order to support MIMO (multiple input multiple output) techniques for robust OWC data transfer.

Upon invitation, a paper [KOO20] reviewing our beam-steered optical wireless system technologies was submitted to the prestigious Philosophical Transactions A of the Royal Society, which is world's oldest scientific journal.

### RADIO-OVER-FIBER

For supporting the picocell network architecture in 5G and beyond-5G networks, multiple broadband mm-wave radio beams need to be steered independently from each other. We designed a system concept feeding the radio signals to the antenna base stations by radio-over-fiber links, which enables optical control of the beam steering. An integrated optical beamforming network has been realized, with a wide bandwidth of up to 6 GHz, capable of independently providing continuous delay tuning to two separate beams modulated on different optical carriers. Up to 90° scanning can be achieved for a 1×4 multi-beamformer at 20 GHz [TRI19]. The initial data transmission experiment shows error-free transmission of a 16-QAM modulated 2 GHz signal in the K-band (18-27GHz) over one channel of the beamformer.

Radio beam steering at high resolution typically is done with phased array antenna structures. It needs many antenna elements and hence many adjustable phase shifters to tune the beam's direction. Using radio-over-fibre techniques, dual-direction optical RF signal driving of the antenna elements and simply-adjustable optical power combiners, we created a novel architecture for optically-controlled radio beam steering which was filed as US Provisional Patent [CAO19a].

By means of spatially multiplexing radio-frequent Orbital Angular Momentum (RF-OAM) wave-modes, the data transport capacity of a radio link can be multiplied without requiring additional (precious) radio spectrum. We designed a novel PIC-based concept for generating/multiplexing/demultiplexing RF-OAM modes which each interface directly with the respective wavelength channel in a fiber. This novel concept has been filed as US Provisional Patent [KOO19c].

**Targets 2020**

- Improve the quality of the mode transfer matrix obtained by these instruments. Improved resolution can reveal in detail the mode coupling and mixing which can enable better insights into mode dependent losses of components.
- Improved insight in mode-dependent loss can enable the design of advanced modulation formats which can exploit the spatial dimension to increase capacity greater than 10 Petabits/s optical transmission systems.

## THEME 1.2 **Data centers and optical interconnects**

*Project leader: Oded Raz*

### HYDROGENATED AMORPHOUS SILICON AND PROGRAMMABLE PHOTONICS

The research on programmable photonics using hydrogenated amorphous silicon is a collaborative project of the ECO and PMP groups.

The main findings from the investigations carried out in 2019 were also related to the objectives defined for 2019. These revolved around the possible relationship between strain and light soaking on free-standing aSi:H membranes. From the investigation we have carried out we have found that free standing membranes (see Figure 3) change their shape under light soaking and annealing which suggests that the underlying mechanism behind the change in refractive index in the anti-reflection coatings and the microring experiments carried out in 2018 is strain-related.

### NOVEL 3D AND 2.5D PACKAGING FOR OPTICS IN DATA CENTERS

The activities related to coupling of light from VCSELs into SiPh waveguides which are part of the PASSION project suffered a critical delay because of processing delays and challenges experienced by one of the project partners. We anticipate that these activities will take place in 2020.

TARGETS FOR 2020

- The work on hydrogenated a:Si is waiting for new staff to be hired. His or her background will partially define the research direction. We expect to continue in the summer of 2020.
- Demonstrate assembly of VCSELs directly coupled to a SiPh DWDM PIC with capacity >1Tb/sec.

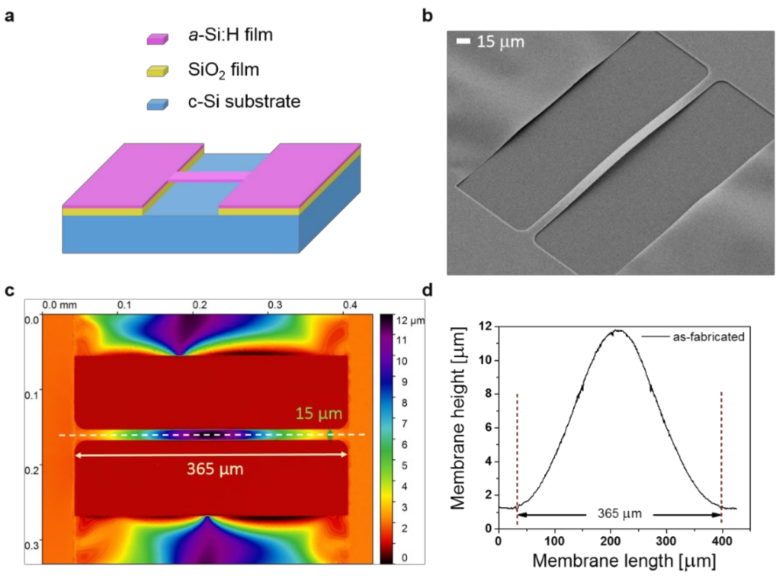



*Figure 3 Hydrogenated amorphous silicon (a-Si:H) free-standing thin-film membrane to study the effects of cycles of annealing and light soaking treatments on strain. a. A simple schematic of the fabricated free-standing bridge structure by patterning and dry etching of a-Si:H (around 220 nm) and then wet etching of sacrificial $SiO_2$ (around 1 µm). b. SEM image showing buckling upwards due to the high compressive stress in the a-Si:H film. c. Using an optical profiler the spatial profile of the free-standing a-Si:H bridge was measured. d. The extracted line profile that goes across the bridge as shown by the dashed white line in (c).*

THEME 1.3 **Optical Switching**

*Project leader: Patty Stabile*

The project is focusing on a lossless, monolithically integrated photonic neuron for all-optical computation. An all-optical neural network implementation, based on all-optical neurons, is expected to offer a route to scalability, however so far no demonstration of a full all-optical integrated neuron with continuous input data sequences has been reported yet. Artificial neural networks are computational architectures where the base model of an artificial neuron is mainly composed of two functions: a weighted addition (linear) function and a non-linear function. Recently, photonic integrated approaches have been proposed to realize the linear and non-linear functions, but so far these implementations have relied on hybrid integration schemes [SHA18], external input lasers [MOU19] and the involvement of power-consuming O/E/O conversions [SHE17], hindering the realization of a scalable photonic neural network. We now demonstrated a complete photonic neuron that is monolithically integrated on an InP SOA (semiconductor optical amplifier)-based single chip. Both the weighted addition and a non-linear function are co-integrated. Moreover, the additional co-integration of a tunable laser allows for an on-chip optimization of the non-linear function. The InP photonic integrated neuron explores the wavelength domain, allows for lossless data processing, opening the way to a scalable all-optical photonic neural network architecture.

The conceived all-optical deep neural network architecture is shown in Figure 4a. Each neuron (detailed in the grey box) receives at its input a number of signals with different wavelengths and it gives as output a signal coded into yet another wavelength. The output of this neuron, together with the outputs at the other neurons of the same layer, are then sent to the next layer of neurons for further processing. This repeats itself for the other layers of the network.

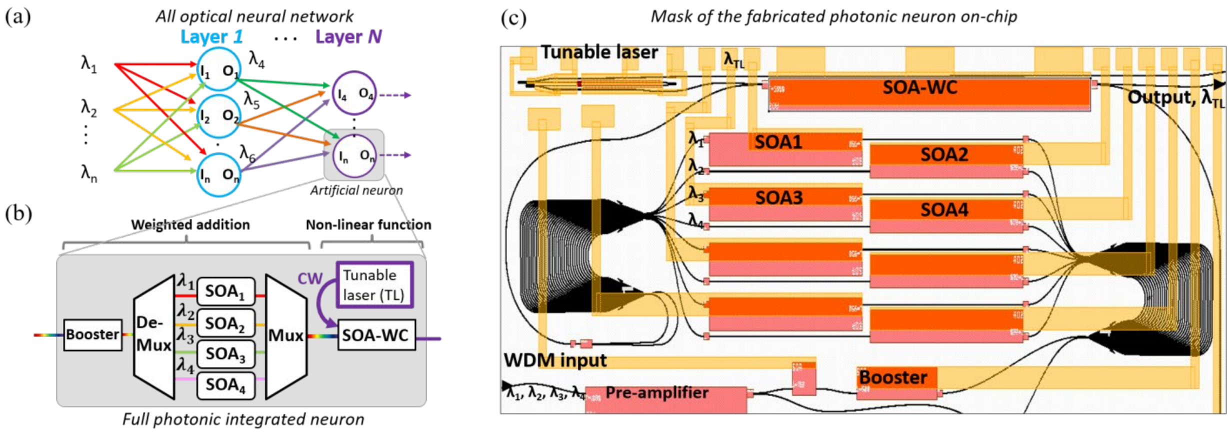



*Figure 4 (a) Representation of the all-optical deep neural network, with white circles being the neurons. (b) Scheme of the implemented monolithically integrated neuron. (c) Mask details of the chip. WC=wavelength converter. CW= continuous wave.*

In an experimental set-up, the full photonic integrated neuron is realized by using a combination of arrayed waveguide gratings (AWGs) and semiconductor optical amplifiers (SOAs) technology. Figure 4b shows the schematic of the implemented photonic neuron. The neuron processes N wavelength division multiplexed (WDM) signals. After pre-amplification, the signals enter a de-multiplexer (De-MUX) which allows access to the individual channels. These are weighted by using the gain variation of multiple SOAs, then a multiplexer (MUX) combines back all the wavelength signals. The weighted WDM signals undergo the SOA-based wavelength converter (SOA-WC), which is employed as optical activation function. The tunable laser is co-integrated in the photonic chip. The SOA-WC converts all-optically the multi-wavelength signal total power into one single wavelength, which represents the neuron output. Although in this first demonstration the SOA-WC provides an inverted signal at its output, an SOA-MZI scheme can be used in the future as non-inverted WC [MOU19]. Figure 4c illustrates the mask details of the complete on-chip integrated neuron which includes the weighted addition circuitry and the SOA-WC. The WC is based on cross-gain modulation [SHI19], with a 2 mm long SOA and a tunable coupled-cavity laser (TL). The TL, centered at 1549.0 nm, provides 0 dBm optical power [DAG15]. The chip employs a combination of SOAs at its input side to increase the SOA linear range. The fabricated photonic integrated chip (PIC) has been processed via an InGaAsP/InP multi-project wafer run.

The input power of the modulated optical data (probe signal) to the wavelength converter is critical for the cross-gain modulation, therefore an input optical power optimization procedure is investigated, by tuning current of booster SOA with a 26 mA range (Figure 5a). Figure 5b shows the measured output signal (blue line) and the expected signal (red line) when the injection current of the booster SOA is set to 7 mA, 11 mA and 20 mA, resulting in an error of 0.15, 0.13, 0.19, respectively. We tested the full photonic neuron operation with 4 WDM input data shown in Figure 5c. Figure 5d illustrates the optical spectrum at the chip output, where the peaks from left to right are at wavelength $\lambda_1$, $\lambda_2$, $\lambda_{TL}$, $\lambda_3$ and $\lambda_4$, for a net on-chip gain of 11.4 dB. The measured photonic neuron output after being filtered and after the O/E conversion is shown in Figure 5e (blue line). The expected results are also reported (red line) in order to estimate the accuracy of the fully integrated photonic neuron.

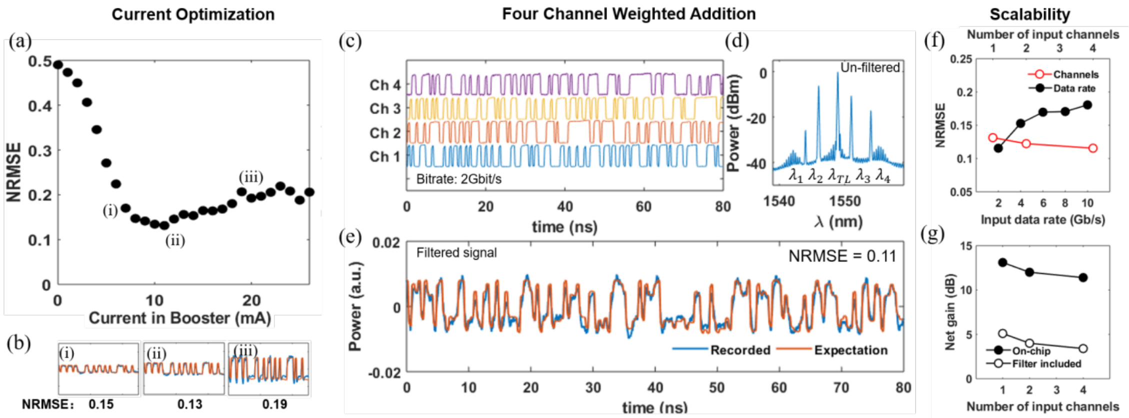


*Figure 5 Current Optimization: (a) NRMSE vs. Current in the booster. (b) Time traces at different injection currents. Weighted Addition: (c) The four input channels. (d) Un-filtered output spectrum. (e) Filtered and detected time traces. Scalability: (f) Error evolution versus the input data-rate (filled circles) and versus the number of input channels (empty circles). (g) Net on-chip gain (filled circles), and if the external filter was co-integrated (empty circles) as a function of the number of input channels.*

In Figure 5f the error gradually increases from 0.11 to 0.18 with the increase of the four input channel data rate from 2 Gb/s up to 10 Gb/s (filled symbols). This trend is in line with the carrier dynamics of both the booster SOA and WC SOA. Figure 5f also includes the error variation (empty circles) when 1, 2 and 4 channels are input to the optical neuron. Figure 5g depicts the net on-chip gain (filled circles), and if the external filter was co-integrated (empty circles), as a function of the number of input channels. The net on-chip gain is calculated considering 11 dB fiber-to-chip total coupling losses. A higher number of input channels offers a higher probe optical power to the wavelength converter, resulting in improved conversion efficiency for the used settings [SHI20].

The all-optical photonic integrated neuron with co-integrated wavelength converter and tunable laser as non-linear function is demonstrated with 4 inputs, resulting in a best-case accuracy of 89% [SHI20,SHI20a]. The achieved lossless neuron operation suggests that a scalable all-optical neural network is possible, based on the co-integration of optical amplifiers and cross-gain modulation effect. The level of accuracy achieved for Gb/s rate level, allowing for 2 orders of magnitude more algebraic operations per energy unit than in a conventional digital processor, suggests the possibility to address in the near future faster time-scale real-time applications.

### TARGETS FOR 2020

- Implement and demonstrate multi-layer all-optical neural network;
- Improve power consumption metrics looking at active elements which are not current injection based or via hybrid component schemes.

## THEME 1.4 **Integrated low loss space-division-multiplexed transceivers**

*Project leader: Chigo Okonkwo*

Performance metrics for Space Division Multiplexing devices such as mode-dependent loss (MDL) could be obtained at a system-level through analysis of the digital filter taps [VEL18, FON13, ROM17] of the multiple-input multiple-output (MIMO) equalizer required to unravel the mixing of the spatial paths transmission. In 2019, we have been busy developing new tools/instruments for gaining more insight from linear device parameters such as insertion loss (IL), group-delay (GD), chromatic dispersion (CD), polarization dependent loss (PDL) and polarization mode dispersion (PMD) of optical devices and systems. This is expected to yield new insights and improved characterization tools leading to better development of optical components.

### ENHANCED MODAL DISPERSION ESTIMATION ENABLED BY OPTICAL VECTOR NETWORK ANALYZERS

Enhanced Modal Dispersion Estimation enabled by Optical Vector Network Analyzers (OVNAs) was developed to better characterize (SDM) fiber-optic components by providing the full polarization-diverse transfer matrix, analysis of which reveals meaningful performance metrics such as cross-talk (XT) and MDL.

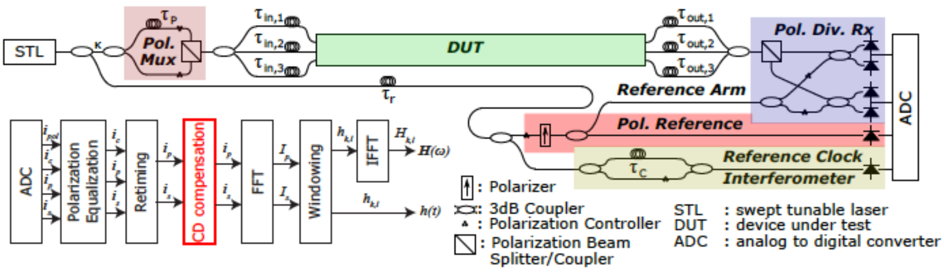



*Figure 6 Experimental setup for the optical vector network analyser*

OVNA employs a swept laser source that is fed to an interferometric structure, resulting in a fringe pattern dependent on the laser tuning rate and interferometer arm length differences. A device under test (DUT), placed in one of the arms will affect the interference pattern according to its transfer function matrix H(ω). From the interference pattern, the 2×2 Jones matrix of a single-mode component can be extracted. Subsequently, linear device parameters such as insertion loss (IL), group-delay (GD), chromatic dispersion (CD), polarization dependent loss (PDL) and polarization mode dispersion (PMD) can be obtained from this matrix. The time-windowing technique proposed for measuring multi-port devices can be applied to capture the 2M×2N transfer matrices of SDM components.

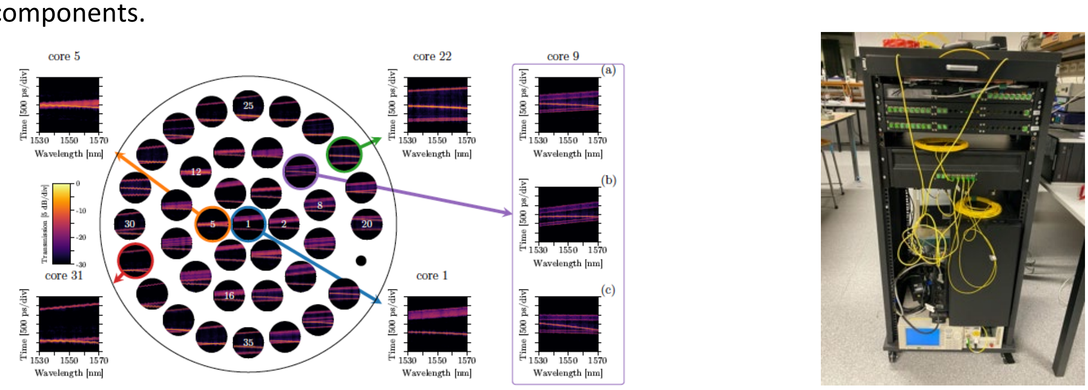



*Figure 7 (a): Spectrograms of a 39-core fiber employing OVNA shows differential mode details and impact of chromatic dispersion [WEE19]; (b): Portable OVNA setup*

Since the components required for the OVNA are all in single-mode domain, a multiplexer-demultiplexer pair is required and characterization of a single multiplexer is not possible since there is no access to the (non-single-mode) SDM domain. This however remains a very useful instrument for obtaining various measurements and has been developed from a bench-top instrument to a portable instrument to be employed for photonic integrated device measurements.

MODAL ANALYSIS OF COMPACT SPACE DIVISION MULTIPLEXERS USING DIGITAL HOLOGRAPHY

This work is an ongoing collaboration with Nokia Bell Labs, US (Paper presented at IEEE Photonics Benelux 2019). In this work, digital holography is introduced as a characterization technique capable of measuring the full polarization-diverse complex field of a device of interest. Since the technique provides access to the intermediary SDM domain, e.g. few-mode or multi-mode, a single multiplexer device can be characterized on its own as opposed to an end system via a multiplexer-demultiplexer. Digital demultiplexing of the measured fields provides a transfer matrix, from which quantitative performance metrics such as MDL and XT can be calculated. A polarization-dependent loss (PDL) emulation stage is characterized to prove the principle of PDL analysis using digital holography.

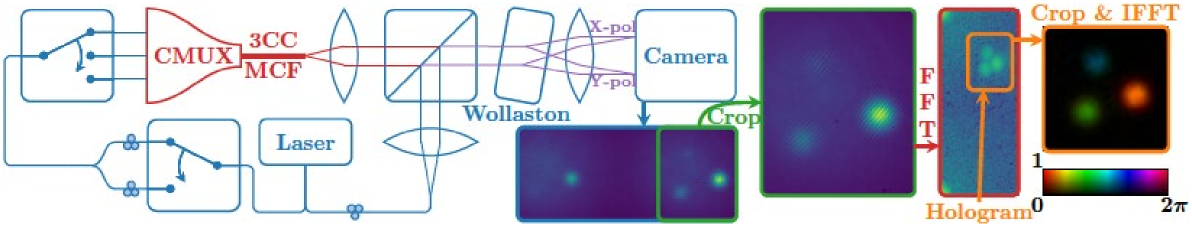



*Figure 8 Preliminary Digital Holography Setup*

Off-axis digital holography capable of measuring the full polarization-diverse complex field emitted from a device-under-test (DUT). The light emitting surface, in this case the facet of a fiber, is placed in a 4f optical setup as shown in Figure 8. The optical setup combines the light emitted from the facet, the signal, with a coherent flat-phase reference beam and images it magnified to the ratio of the lenses on the surface of the infrared camera. A Wollaston prism is used to spatially split both polarizations. The reference beam is placed under a slight angle, hence off-axis digital holography, which leads to fringes produced by the beating between the reference beam and the signal light. Even though the camera only records the intensity of incident light and would thus destroy any phase information, it is still preserved in the fringe pattern and can therefore be extracted by subsequent digital signal processing (DSP). The DSP chain for digital holography starts with masking or cropping of a region of interest of the recorded camera frame as shown in the insets of Figure 8. The Fourier transform is used to convert this region from the spatial domain, real-space, to the angular domain, k-space. An inverse Fourier transform is used convert from k-space to real-space where now the full complex, i.e. both amplitude and phase, scaled image of the facet of the DUT is at our disposal. If the measurement apparatus is calibrated and aligned perfectly, this field can be used for subsequent processing. However, residual phase errors will be present in the extracted field if the measurement apparatus is not perfectly aligned. For example, tilt of the camera can lead to linear phase errors. If the DUT or reference is not perfectly in the focal point, this can lead to a quadratic phase front. These linear and quadratic phase errors can be estimated and subsequently removed, revealing the correctly extracted field. The phase-corrected extracted fields are considered the end result of the digital holography since the full polarization-diverse complex field present at the facet of the DUT is known. However, these fields can be used for further processing and analysis, one particularly interesting use is the construction of a transfer matrix through digital demultiplexing. A suitable modal basis is chosen, in this case a Gaussian spot with appropriate beam width, and the overlap integral with the extracted field is calculated. Since this overlap is calculated digitally and the modal basis can be chosen freely, for example the mode profile of an optical fiber or device of interest, this technique is called digital demultiplexing. These overlaps reveal one column of the transfer matrix (Figure 9) since the extracted field is the measured output of one particular input port and polarization of the DUT. The full transfer matrix is obtained when the measurement is repeated for each input port and polarization. Since the extracted fields are discretized, the overlap integral is replaced by a double sum and each transfer matrix element, one for every input and mode combination for both polarizations, is calculated

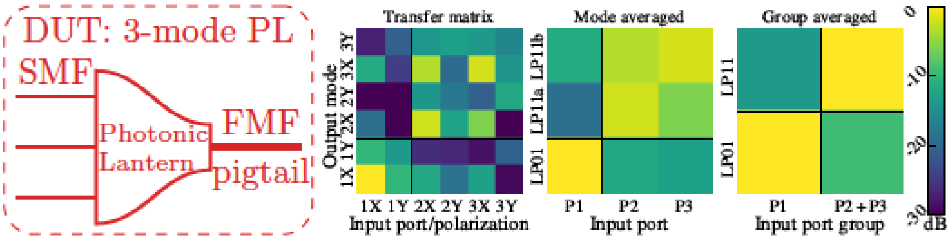



*Figure 9  Device under test with the full transfer matrix revealing spatial mode mixing performance*

A major advantage of digital holography over other measurement techniques is digital demultiplexing, which allows for the characterization of a single multiplexer device as opposed to a pair. A single three-mode photonic lantern (PL) is characterized, yielding the amplitude and phase of the field emitted from the device for each input port and polarization. Further analysis provides the full polarization diverse complex transfer matrix used to calculate quantitative performance metrics which cannot be inferred from raw camera images. The mode-selectivity of the PL qualitatively observed from the raw camera images, is quantified by cross-talk which is calculated to be 13.1 dB at 1550 nm. Mode-dependent loss, which cannot be evaluated qualitatively, is measured to be 2.2 dB. Additional measurements at other wavelengths need to be carried out at a later stage to evaluate the broad-band operation of the instrument and its performance at other wavebands.

### TARGETS FOR 2020

- Improve the quality of the mode transfer matrix obtained by these instruments. Improved resolution can reveal in detail the mode coupling and mixing which can enable better insights into mode dependent losses of components.
- Improve the insight in mode-dependent loss. This can enable the design of advanced modulation formats which can exploit the spatial dimension to increase capacity greater than 10 Petabits/s optical transmission systems

## THEME 2 NANOPHOTONIC INTEGRATED CIRCUITS

*Theme coordinator: Kevin Williams*

Highlights:

- Grating antenna for LiDAR beam steering with record-high 0.05° spatial resolution [WAN19]
- First publications from external MPW users on the topic of InP ring resonators for quantum processing [KUM19, KUM19a]
- Invited publications on active component integration on the IMOS platform [TOL20, JIA19]
- First demonstration of integrated nano-opto-mechanical sensor with wide optical bandwidth (to be published in Nature Communications [LIU19])

### THEME 2.1 **Generic integration platform for photonic ICs on silicon**

*Project leader: Yuqing Jiao*

The successful demonstrations of the IMOS twin-guide SOAs and lasers in 2017 and 2018 have attracted high levels of attention worldwide. In 2019, the team has been invited to write journal review papers in IEEE Journal of quantum Electronics [TOL20] and Physica Status Solidi (a) [JIA19], as well as to present multiple invited talks in international conferences [WIL19, TOL19, JIA19a, JIA19b, JIA19c, JIA19d].

In 2019, significant effort has been put in to exploit the potential of this platform. Inspired by our industrial partners, we have identified the free-space communication and non-contact sensing as the vehicles to demonsatrate the capability of the platform. IMOS's unique combination of lasers, amplifiers with nanophotonic waveguides and gratings offers a route to optical beam control from a single membrane layer. Based on this, we have successfully received an EC-ERC Proof of Concept grant IMOS4ALL to explore in this direction. We have implemented the most comprehensive set of active and nanophotonic building blocks as created from this Theme 2 into a nanophotonic process design kit (PDK) including the mask library, preliminary design rules and component models. The PDK will be used to create validation circuits for free-space applications, which will be fabricated from the internal multi-project wafer (MPW) run planned within the IMOS4ALL project.

#### GRATING-BASED ANTENNA FOR LIDAR

Additionally, we have also obtained a significant achievement at the component level for an important, emerging free-space application: LiDAR. We have designed and successfully demonstrated a grating-based optical antenna on IMOS with excellent beam quality and steering capability [WAN19]. The schematic of the grating design is shown in Figure 10a. The device is based on the standard 300nm-thick IMOS waveguide, with $SiO_2$-based gratings deposited and patterned on top of it. The $SiO_2$ grating layer is only 100 nm in thickness, forming a weakly coupled grating which is crucial for achieving ultra-long grating lengths for narrow far-field beam width. Compared to conventional shallow etching into the semiconductor core for silicon photonics, the $SiO_2$ cladding grating on InP membrane offers an extremely fabrication-tolerant design. The grating etch depth is expected to be precisely defined by the $SiO_2$/InP interface over the entire wafer scale as well as from run to run, owing to the naturally high selectivity between InP and $SiO_2$ in $CHF_3$-based, dry-etching processes. We also placed a metal back-reflector beneath the grating to boost the optical coupling efficiency from waveguide to above 90 %. The fabricated device is shown in Figure 10b. The measured far field beam profile of a 2 mm long grating showed a record narrow beam width of only 0.05°, which is the best among InP based beam steerers and competitive to those in silicon photonics. When tuning the input

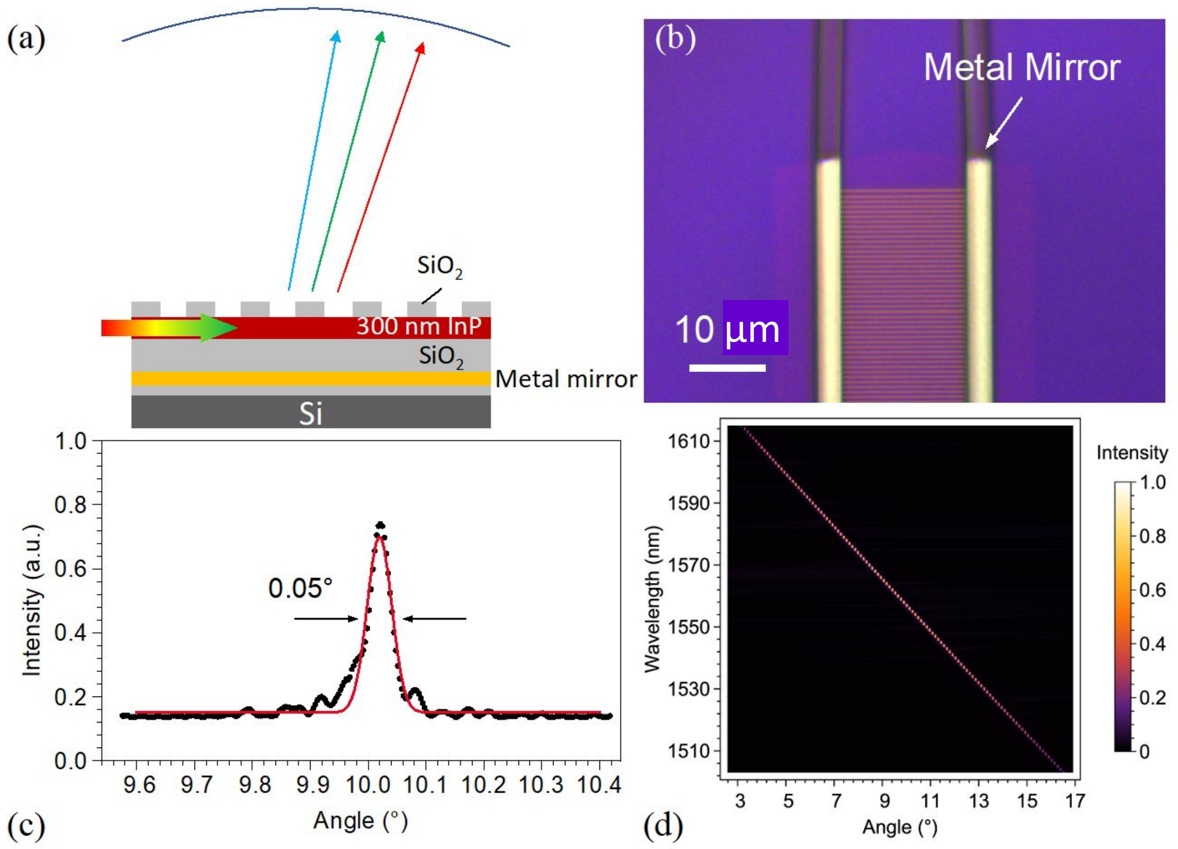



*Figure 10 (a) Schemetic illustration of the grating antenna on IMOS. (b) Top view of a fabricated device. (c) Far-field beam profile showing record-narrow beam width of 0.05°. (d) Measured steering map (beam angle vs. laser wavelength) of the device.*

laser wavelength over 100 nm, the grating emission angle can be steered over 13.5°. The next step is to integrate this grating antenna with on-chip amplifier and phase modulator arrays to form a complete beam steerer PIC for LiDAR application.

## PHASE MODULATORS BASED ON ELECTRO-OPTIC POLYMERS

Phase modulators are essential elements for both communications and free-space beam steering in LiDAR. We have proposed the electro-optic (EO) polymer-based slot waveguide phase modulator (a collaboration with Lightwave Logic), see Figure 11a, and have made progress in functionalizing of the polymer on IMOS slot waveguides. The coating and poling process of the polymer on InP material surface is studied for the first time. We have successfully developed the process on InP membrane slot waveguides with good polymer adhesion and filling into the 100 nm wide slots (see Figure 11b). Preliminary DC characterization of the EO-polymer phase modulator showed an effective EO coefficient ($r_{33}$) of 60 pm/V for the polymer and a $V_\pi L$ product of 4.5 V·mm. The $V_\pi L$ product is mainly determined by the mode overlap with the polymer and the $r_{33}$ of the polymer material. The EO polymer we used is aiming for moderate EO coefficient with high reliability and lifetime. We can use polymers with higher EO coefficient to reduce the $V_\pi L$ product.

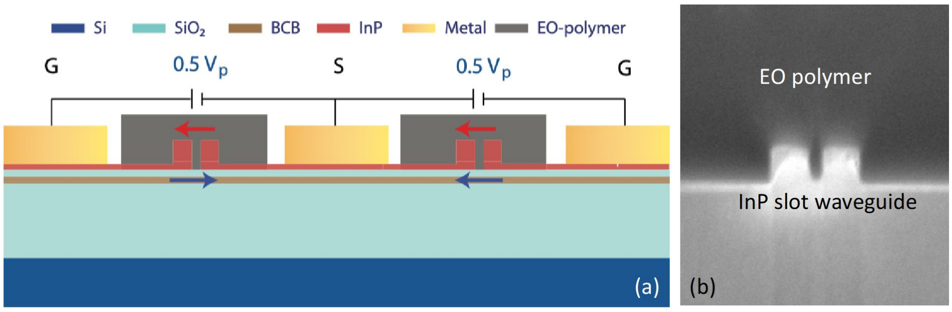



*Figure 11 (a) Schematic of the slot phase modulator. (b) Picture of a fabricated slot modulator waveguide filled with EO polymer.*

## OTHER IMOS COMPONENTS

In 2019 we reported the latest technology developments for our DUV scanner lithography on the IMOS platform. We have benefitted from the high resolution and high reproducibility of this tool in realizing passive membrane waveguides. We have developed the lithography process, especially the resist reflow process, for the InP membrane platform. A record-low waveguide loss of 1.8 dB/cm was reported [ENG19] using this DUV process. We also observed significant performance enhancement on complex devices such as arrayed waveguide gratings (AWGs) as compared with conventional EBL processes, showing reduction of the insertion loss of 2 dB and reduction of the crosstalk of 8 dB [ENG19a].

On-chip reflectors are essential elements for building lasers, resonators and interferometer circuits. We have proposed and developed a novel photonic crystal (PhC) based reflector with reflectivity as high as 98 % and broad optical bandwidth of over 100 nm [REN19]. Using this PhC reflector, we have designed and demonstrated a compact reflective AWG, which offers similar performance as transmission-type AWGs but with nearly halved footprint [ZHA19].

The collaboration with Prof. Hon Tsang from Chinese University of Hong Kong continues, on the topic of InP membrane resonators for quantum communication. We have studied the spontaneous four-wave mixing (SFWM) mechanism in InP membrane micro-ring resonators and its use for generating paired single photons. We discovered that the single-photon generation rate and the heralding efficiency from the InP membrane resonators are comparable to the state-of-the-art in silicon-based resonators [KUM19, KUM19a]. The pump power needed in an InP membrane resonator to achieve this efficiency is about 10 times lower than in silicon-based resonators, thanks to the higher third-order ($\chi^{(3)}$) nonlinearity in InP. We also discovered that at higher pump power the two-photon absorption (TPA) and the free-carrier absorption (FCA) play important roles in the InP membrane resonators. We are investigating methods to suppress the free carrier induced loss effect in InP membrane.

## TARGETS FOR 2020

For 2020, the main research focus is the development of the butt-joint integration technology, which will enable taper-free active-passive interfaces for high-speed compact cavity lasers. We have designed the first-generation butt-joint SOA layerstack, which is now being fabricated in the cleanroom. We will continue integrating the DUV scanner technology into our membrane process flow. For circuit-level development, we focus on the RF optimization of the EO-polymer slot phase modulators in MZI configuration and the design of a LiDAR beam steerer circuit based on the developed grating antenna.

THEME 2.2 **Ultralow-power components**
*Project leader: Andrea Fiore*

NOVEL SENSORS BASED ON THE IMOS PLATFORM

Based on the progress in IMOS technology, two novel types of integrated sensors were developed within the PSN group, in collaboration with PhI. The first sensor is a nanomechanical displacement sensor based on a three-dimensional 4-waveguide directional coupler (see Figure 12a&b). The vertical displacement of a nanobeam is transduced into a differential change in transmission at the two outputs. The sensor was integrated with a waveguide detector in the IMOS platform. When injecting a laser beam into the input waveguide, we are able to measure the thermal motion of the nanobeam through the corresponding peak in the photocurrent noise spectrum (Figure 12c). By comparing the integrated power in the peak and the noise floor, we deduce a displacement imprecision of 45 fm/Hz$^{1/2}$, limited by the pick-up electrical noise in the setup. This optomechanical sensor has two remarkable features, namely a very large optical bandwidth of >80 nm (see Figure 12c), which enables the use of simple read-out lasers, and the integration of the detector, with the further possibility of integrating the laser source as well [LIU19]. Such a compact sensor could find applications as smart tip in parallel atomic-force microscopy systems (ongoing collaboration with TNO and other partners).

A second type of sensor is a spectral sensor based on an array of resonant-cavity detectors on IMOS (Figure 12d). These detectors, based on Fabry-Perot cavities with an embedded InGaAs photodiodes, are designed to present resonances in the near-infrared (1000-1700 nm), which are lithographically tuneable across the array (Figure 12e). We calculate that, by collecting the photocurrent signals from the different pixels, it will be possible to reconstruct the spectral properties of many important organic materials, and thereby their biochemical characteristics (for example, sugar content in leaves or fruit). This would provide an integrated, low-cost sensor for the agrofood and chemical industry. Sensing experiments are planned in collaboration with relevant partners and a patent has been submitted [FIO19].

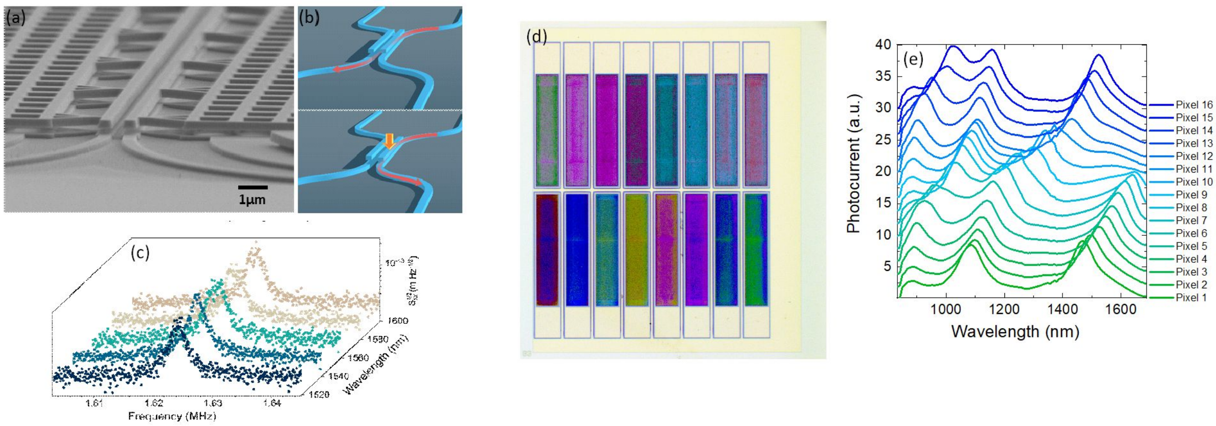



*Figure 12 (a) SEM image of a nanomechanical IMOS sensor; (b) Sensing concept; (c) Thermomechanical motion observed in the noise spectrum; (d) Optical image of an array of IMOS resonant-cavity detectors for spectral sensing; (e) Measured photocurrent spectra from the 16 pixels.*

LAYERED 2D SEMICONDUCTORS

Layered two-dimensional (2D) materials have promising optical and optoelectronic properties for both passive and active components in photonic integrated circuits due to strong light-matter interaction and the ability to control their optical properties electrically. The layered crystal structure can facilitate the integration of 2D materials into devices without the introduction of defects due to lattice mismatch. Layered 2D semiconductors with a bandgap in the optical telecommunications bands (1200–1700 nm) are however still scarce. Examples are few-layer black phosphorus and monolayer molybdenum telluride, but both suffer from environmental and photo-stability issues.

In 2019, we published our results on layered titanium trisulfide as a stable 2D material emitting photons around 1360 nm, covering the E- and O-bands [KHA19, BAS19]. We demonstrated that its emission is of excitonic origin and anisotropic due to the quasi-one-dimensional nature of the crystal, resulting in linearly polarized emission. Additionally, using few-layer black phosphorus, we have shown spectrally tunable emission. Through laser-induced defect creation and encapsulation, the emission spectrum can continuously span the near- and mid-infrared: from 780 nm (monolayer) to 1500 nm (four layers) and possibly beyond towards 4 μm (bulk). This is a promising strategy to fabricate spectrally engineered devices within a single material platform.

Another development is the use of atomically thin materials for guiding light. We have theoretically shown that it is possible to use semiconductor-insulator-semiconductor heterostructures as thin as 2 nm as waveguides for visible light due to the strong excitonic response of monolayer transition metal dichalcogenides. The structures show promise for electrical tunability.

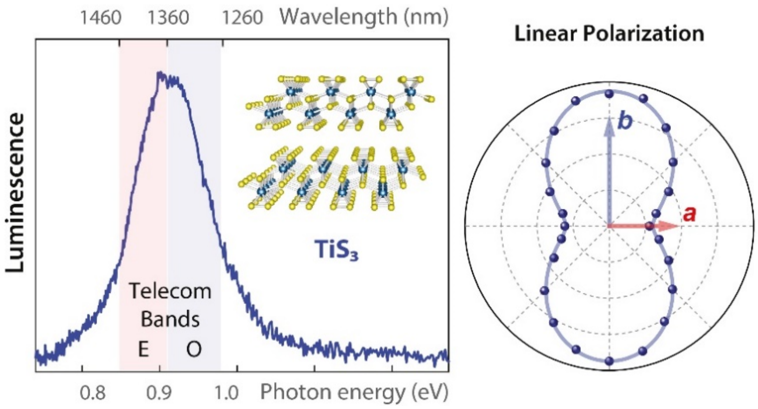



*Figure 13 Titanium trisulfide consists of atomically thin layers with in-plane, quasi-one-dimensional character. It displays photostable photoluminescence peaking at 1360 nm and shows linear polarization.*

TARGETS FOR 2020

- Integration of a displacement sensor on top of an IMOS MPW run including lasers and detectors.
- Further improvement of spectral sensors based on IMOS resonant-cavity detectors (linewidth, spectral response) and first test in sensing applications.

THEME 3 ULTIMATE CONTROL OF MATTER AND PHOTONS

*Theme coordinator: Paul Koenraad*

**Highlights**:

- Hex-SiGe shows a similar radiative efficiency as a III/V semiconductor (published in Nature, [FAD20])
- All-optical switching of magnetization 'on the fly' into a magnetic racetrack (published in Nature Communications [LAL19])
- Deterministic laser-induced writing of magnetic information assisted by spin currents [HEE20]
- Significant reduction of the surface recombination of Ge surfaces by $Al_2O_3$ and a-Si:H nanolayers
- Demonstration of lattice resonances in dielectric metasurfaces; first experiments show room-temperature lasing
- Exciton-polaritons observed with electric and magnetic character inherited from the cavity

THEME 3.1 **Quantum effects in nanophotonic devices**

*Project leader: Jaime Gómez Rivas*

Our goal is to exploit quantum effects in strongly coupled systems to achieve lasing at low thresholds. Strong coupling of excitons in organic materials and cavity photons in arrays of nanoparticles results in the formation hybrid states, known as exciton-polaritons, which are a quantum superposition of light and matter. Exciton-polaritons can condense into the ground state at sufficiently high densities, which leads to a coherent emission without the need for population inversion. This coherent emission is known as polariton lasing. Quantum effects responsible for condensation and polariton lasing can be exploited to reduce the threshold of non-linear emission compared to traditional lasers, which may lead to the realization of integrated electrically-driven polariton lasers.

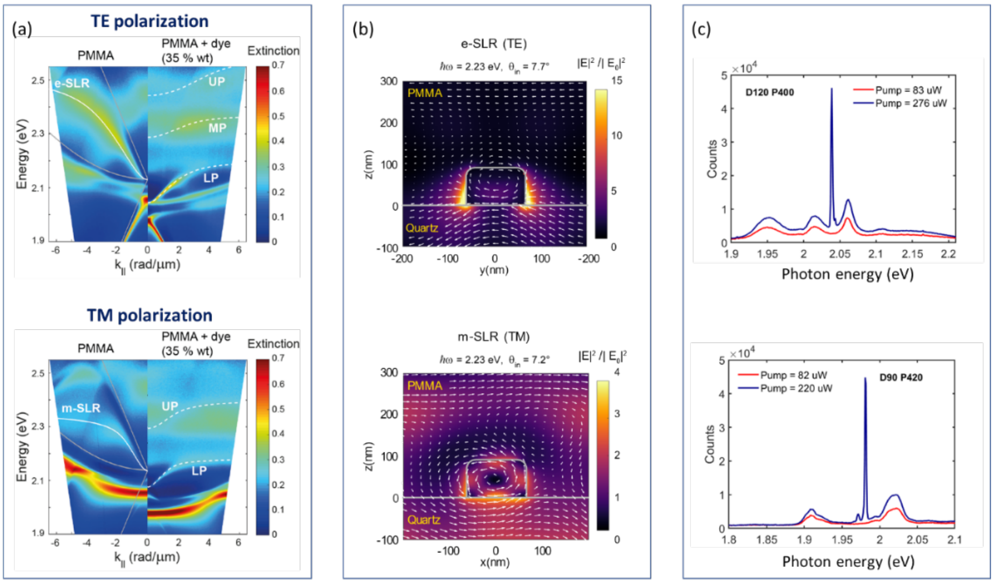



*Figure 14 Demonstration of strong coupling and polariton lasing in semiconductor nanoparticle arrays with a deposited layer of PMMA doped with organic dye at high concentration. In panel (a) the measured optical extinction (i.e. 1-transmission) is shown for the TE and TM polarizations as a function*

*of the incident in-plane wave vector of light $\boldsymbol{k}_{\parallel}$. For both polarizations the reference (undoped PMMA) is shown for negative wave vectors, and the white solid line represents the dispersion of the cavity resonance. Exciton-polaritons are formed in the presence of the organic dye. In panel (b) the electric and magnetic character of the cavity resonance is shown for each polarization. In panel (c) the emission spectra of two samples are shown for pump powers below and above the lasing threshold.*

The coupling strength between the photons in the cavity and the excitons in the material depend on the losses in the system. Therefore, we have moved our research focus from metal cavities, which are inherently lossy, to semiconductors where the losses can be significantly reduced and even suppressed [CAS19, MUR20]. In 2019 we have demonstrated the strong coupling of organic excitons with semiconductor nanoparticle arrays (see Figure 14a) [CAS20]. The nanoparticles support electric and magnetic resonances (see Figure 14b). This character is inherited by the exciton-polaritons that are formed, which gives an additional degree of freedom and allows a control on the properties of exciton-polaritons.

Our most recent experiments have shown that lasing action is supported in these structures (see Figure 14c). However, the rapid photodegradation of the sample has been a limiting issue for detailed investigations, hampering further experiments that are needed to elucidate the properties of the lasing (threshold, coherence, temporal dynamics). We are working towards solving this issue by changing the repetition rate of the pump laser and the position of the excitation on the samples

Additionally, the low losses of semiconductors allow the realization of the so-called bound states in the continuum (BICs). BICs are optical modes that cannot couple to radiative channels, so quality factors diverge to infinity in the absence of material losses (see Figure 2a and 2b). In collaboration with the theoretical group of dr. Jose Sánchez-Gil at IEM-CSIC (Spain), we are designing nanoparticles arrays made of silicon that show a wide tunability of BICs from the visible to the infrared. These arrays are fabricated in collaboration with dr. Shunsuke Murai from Kyoto Univerisity at Japan. Using BICs as cavity for light-matter interaction will bring losses to an unprecedented low level, and enable ultralow thresholds in polariton lasers.

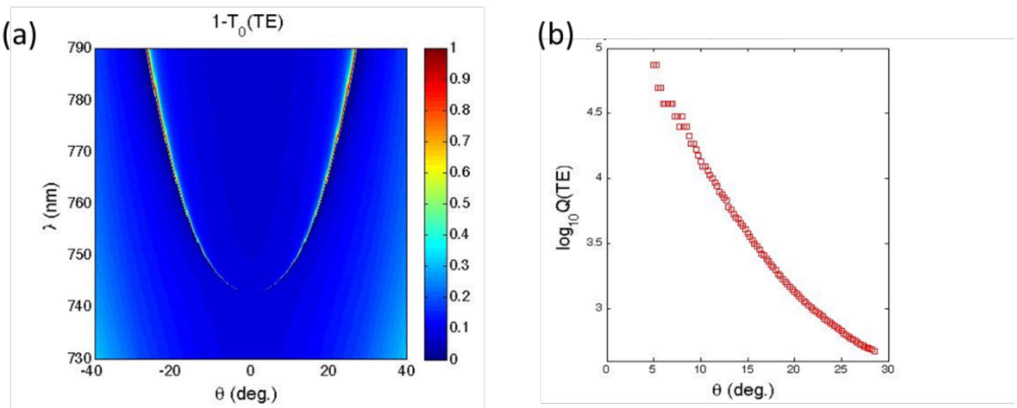



*Figure 15  Bound states in the continuum (BIC) in a semiconductor nanoparticle array. (a) The cavity resonance of the array, with a vanishing extinction as the incident angle approaches zero (normal incidence). At normal incidence, the resonance disappears, indicating that the cavity is decoupled from any radiative channel that leaks the energy stored in the cavity into the far-field. (b) Quality factor of the resonance vs angle.*

THEME 3.2 **Hybrid approaches combining photonics and spintronics**
*Project leader: Bert Koopmans*

This subproject aims to offer novel functionalities for PICs by creating MagnetoPhotonic building blocks [KOO18a]. We envision that by combining ultrafast magnetization dynamics, spintronic phenomena, and photonics, we can create high-density magnetic memories where photonic data can be stored and retrieved at high rates without the need for intermediate electronics. In this phase we focus on better understanding the mechanisms behind the optical manipulation of magnetic materials, as well as integrating these magneto-optical phenomena with PICs. More specifically, we focus on femtosecond laser induced all-optical magnetization switching in free space to write data, while we investigate novel magnetic claddings on photonic waveguides for data reading.

In recent years we have shown that all-optical switching (AOS) of magnetic bits using femtosecond (fs) laser pulses is a feasible way to energy-efficiently store data in a magnetic racetrack [LAL17,LAL19]. Building on this, in the past year we have made an important step towards the implementability of AOS. We have done this by showing that we can move from the typical toggle switching behavior to a system where a desired magnetization state can be written controllably regardless of the initial state [HEE20]. By combining the synthetic ferrimagnetic Co/Gd bilayer used in previous work with a ferromagnetic reference layer (as seen in Figure 16), a preferential direction for switching is introduced. For low incident laser pulse energies we find switching which is purely one-directional, while for higher energies the familiar toggle switching behavior is recovered. The difference between threshold energies can already be increased to more than 25% with straightforward engineering of ultrathin (nm) magnetic multilayers. By using a well-defined sequence of either one or two laser pulses we have successfully shown that both 'bit' states of the Co/Gd bilayer can indeed be controllably written, regardless of the initial state, as seen in Figure 16. At the same time we are continuing work to find the ultimate data writing rates which can be achieved using AOS, with preliminary results already indicating potential speeds of up to 20 GHz.

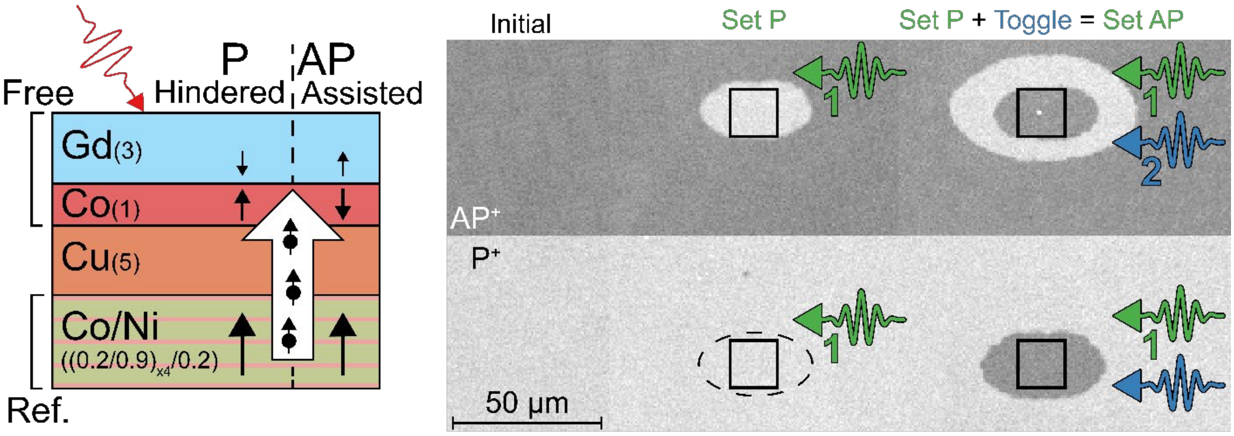



*Figure 16 Demonstration of deterministic writing of magnetic bits using fs laser pulses. Left image shows the sample structure, where numbers between parentheses are layer thicknesses in nm. The reference layer provides a symmetry breaking for switching, such that switching is one-directional for low laser pulse energies. The right image shows a demonstration of writing both states of the free layer using one laser pulse or two laser pulses with different energies. Light and dark contrast indicate the parallel or antiparallel magnetization state respectively. The areas in the black squares are controllably written in the desired direction regardless of the initial state. [HEE20]*

Furthermore, we investigated the physical mechanism that drives AOS of Co/Gd bilayers on a fundamental level [BEE19a]. Motivated by our experiments which showed that AOS of synthetic-ferrimagnetic bilayers can be achieved for a large range of the ferromagnetic (e.g., Co) layer thickness, we developed a theoretical framework to understand the underlying physics. The model showed that the laser pulse first induces switching of the magnetization near the Co/Gd interface. Subsequently, the switched region is extended throughout the entire bilayer driven by an efficient transport mechanism. This propagating mechanism can succeed independently of the Co layer thickness and makes the switching process of Co/Gd bilayers very robust, which gives more freedom in multilayer engineering. Finally, more complex simulations showed that intermixing at the Co/Gd interface, which was expected to be a disadvantageous side effect of the fabrication process, actually enhances the efficiency of the propagating mechanism in the Co/Gd bilayers [BEE19b]. Hence, the recent theoretical studies proved the robustness of AOS in Co/Gd bilayers fundamentally and emphasized once again that the Co/Gd bilayer is an ideal candidate to facilitate the integration of single-pulse AOS in future magnetic memory devices.

The magnetic memory materials whose magnetization characteristics briefly presented above were utilized as claddings on integrated photonics devices. The magnetic information in these claddings can be 'read' by utilizing mode conversion due to the Magneto-Optic Kerr Effect (MOKE). Collaboration between the FNA group and the PhI group provided the knowledge required for integrated photonic device design and fabrication. Simulations of wave guiding media that considers interaction of light with perpendicularly magnetized claddings, revealed that the mode conversion due to MOKE is very small. Therefore the design of photonic devices prioritized device's susceptibility to: the small amount mode conversion and the sign of this conversion. The latter is essential for the determination of the magnetization direction in the cladding, and thus the 'reading'. Figure 17 shows a device design where an external laser source couples-in and out via mode selective couplers, and a Mach-Zehnder Interferometer (MZI) is integrated. A specific range of wavelengths in the telecom range can be used as input. The additional path length allows a controlled phase change in the upper arm of the interferometer thus causes an intensity oscillation with a known frequency upon a wavelength scan. This expected oscillation later is used as a lock-in like technique to increase the sensitivity. In addition, the interference between high and low intensity signals is used to boost the latter. Mathematical models of an ideal version of the presented design revealed that MOKE as small as 0.02 degrees rotation can be detected. When imperfections in functioning were taken into account such as polarization conversion of only 10% and noise levels of 2%, the detectable signal is achieved when Kerr rotation is minimum 0.2 degrees which is foreseen to be achievable through the mentioned simulations [BOO20].

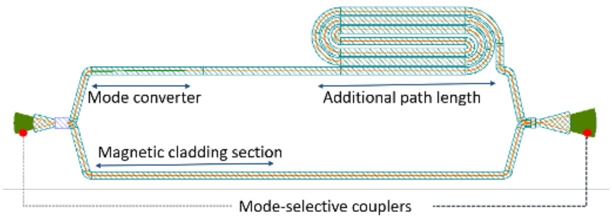



*Figure 17 Representation of a design for Integrated MagnetoPhotonic devices. Light is coupled-in and out through the grating couplers that are selective to TE (Transverse Electric) or TM (Transverse Electric) modes. Light is split into two arms in a functionalized Mach-Zender Interferometer structure where the upper arm contains a region where light polarization is rotated 90 degrees so that the TE mode is converted into TM (and vice versa) and an additional path length for delaying the arrival of light. The lower arm contains a region which coated with magnetic claddings that will be the memory containing part of the device.*

TARGETS FOR 2020

- Optimizing layered magnetic racetrack materials for information propagation at > 500 m/s.
- Further integration of magneto-optical and opto-magnetic functionality with photonic waveguides.

THEME 3.3 **Nanomanufacturing for photonics**
*Project leader: Erwin Kessels*

The photonics nanomanufacturing research within this program is aimed at the atomic scale processing of materials. Most prominently the research focuses on the atomic layer deposition (ALD) of nanolayers, although other deposition and etching techniques, and combinations thereof, are also investigated depending on the specifications of the applications. In previous years, the set of nanolayer materials was significantly extended through the development of new ALD processes (PhD thesis work of Martijn Vos (graduated in November 2019, [VOS19])

In the last year, the focus has shifted to passivation of germanium nanopillar- and nanowire-based devices and the collaboration between PMP and AND groups was further strengthened, building on previous work on InP surface passivation [BLA17]. The goal is the reduction of the surface losses to enable the next step in the roadmap: demonstration of the first optically pumped SiGe nanowire laser. We conducted a systematic research on the surface passivation of germanium by plasma-enhanced ALD of aluminum oxide ($Al_2O_3$) and plasma-enhanced CVD amorphous silicon. We demonstrated the deposition of highly conformal $Al_2O_3$ films on SiGe nanowires (Figure 18a). The surface recombination velocity was studied on planar germanium substrates which revealed that the surface recombination velocity at the native germanium surface ($GeO_2$) could be reduced by one order of magnitude using a combination of a plasma grown germanium oxide in combination with an $Al_2O_3$ capping layer. Repetition of this experiment on hexagonal germanium nanowires yielded a substantial improvement in photoluminescence intensity (Figure 18b). An additional asset of this $GeO_2/Al_2O_3$ passivation scheme is the temporal stability it provides to the surface properties. The latter provides a solution to the observed decline of the Ge nanowire's photoluminescence over time (Figure 18b). Like for silicon we found that negative fixed charge is present in the $Ge/GeO_2/Al_2O_3$ stack, which has a density of about $Q_f = -1.5 \cdot 10^{12}$ $cm^{-2}$. This fixed charge contributes to field-effect passivation at the $Ge/GeO_2$ interface.

We also explored Si-based passivation by means of plasma-enhanced CVD amorphous silicon (a-Si:H). While conformality of CVD on high aspect ratio nanowires can be challenging, preliminary results showed that also this different material class can also provide a significant improvement in photoluminescence (Figure 19a). We are most proud about the extension of our passivation knowledge from silicon to germanium. The latter efforts are expected to pay off in the future research on the more complicated system that hexagonal silicon-germanium nanowires entail.

Another goal of the photonics nanomanufacturing program is gaining atomic-level growth control over the class over materials known as 2D transition metal dichalcogenides. These layered compounds include e.g. molybdenum disulfide ($MoS_2$) and tungsten disulfide ($WS_2$), which are atomically thin direct-gap semiconductors that exhibit luminescence in the red part of the visible spectrum. In addition, the emission spectrum of these materials can be tuned to the optimal wavelength for specific photonic applications or devices by means of alloying. By mixing two layered compounds such as $MoS_2$ and $WS_2$ together, an alloy is obtained. Typically, such an alloy has a luminescence emission wavelength intermediate to those of the pure constituents.

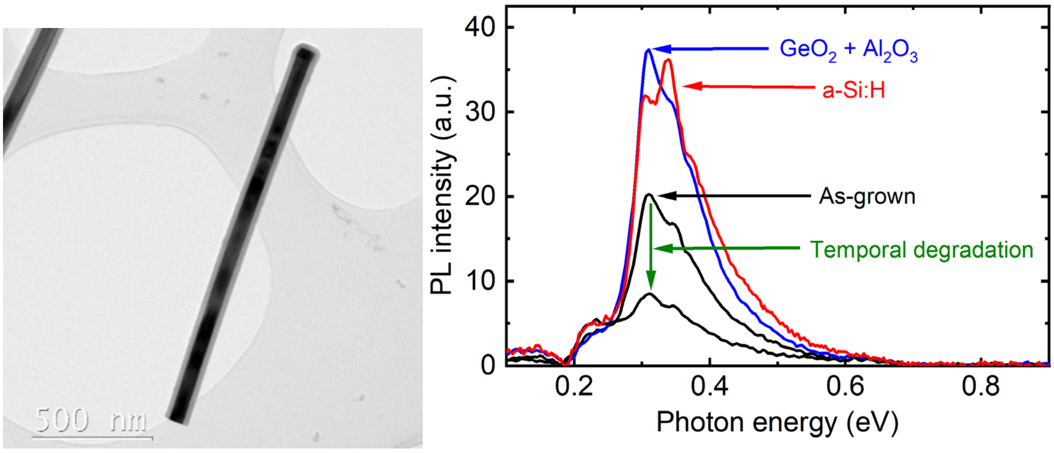



*Figure 18 (a) Illustration of the conformal surface coating ALD Al2O3 can provide for hexagonal Ge and hexagonal SiGe nanowires. (b) Photoluminescence intensity of hexagonal germanium nanowires with a $GeO_2/Al_2O_3$ and a-Si:H passivation nanolayers. As reference, the photoluminescence intensity of the as-grown nanowires is shown including the observed degradation of these wires without capping layer.*

In last year's report, we showed that by using ALD, we could achieve growth of $Mo_{1-x}W_xS_2$ alloys with excellent control over the alloy composition. We also showed that the luminescence of these alloys does not behave like in typical alloys. Instead, the emission wavelength is dominated by the alloy constituent with the lowest bandgap (in this case $MoS_2$). This can be interpreted as a result of nanoscale clustering of the constituents of the alloy, enabled by the comparatively low deposition temperature (450 °C) used in our process.

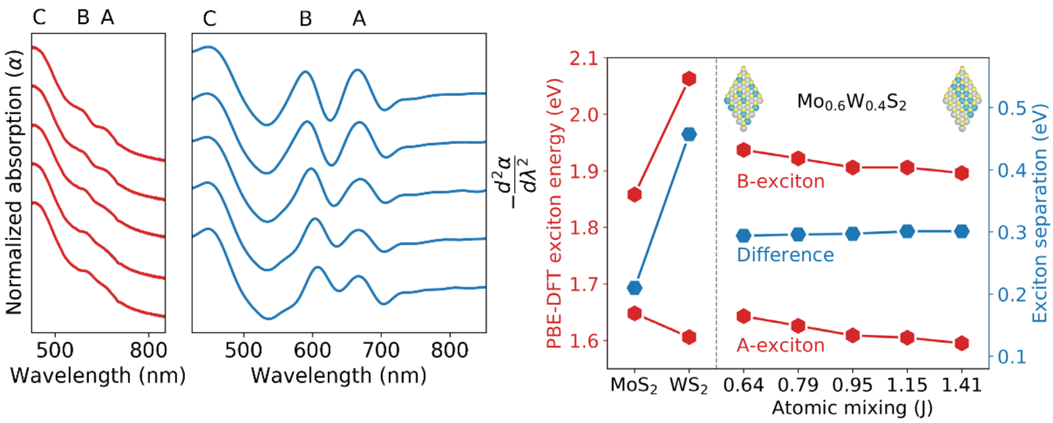



*Figure 19 (a) Optical absorption spectra of $Mo_{1-x}W_xS_2$ alloy films as a function of their atomic mixing (finest mixing at the top). The peaks correspond to the fundamental excitonic transitions and are labeled A, B and C. The energy of the B-exciton is seen to shift as a function of the atomic mixing. (b) Theoretical calculation of the exciton energies of $MoWS_2$ alloys as a function of their nano-scale clustering. The shift in B-exciton is similar in magnitude to the measured shift, supporting the hypothesis that this shift is caused by atomic-scale clustering in the alloy.*

In 2019, we have investigated this clustering in layered alloys in more depth using optical transmission spectroscopy and theoretical calculations. From the absorption spectra we learned that the electronic structure of the alloys changes with clustering, even though the luminescence wavelength is unchanged. These experimental results (Figure 19a) were correlated with electronic structure calculations (Figure 19b) using density functional theory, which confirmed that the observed electronic changes can be attributed to the degree of nano-scale clustering within the alloys. In conclusion, transition metal dichalcogenides are promising materials for future photonic applications. Our results so far indicate that we are able to control the atomic-level structure and ordering of these materials by atomic layer deposition. We anticipate that our technique of controlling the atomic ordering of alloys extends to other material systems beyond $Mo_{1-X}W_XS_2$, and we intend to further investigate the influence of atomic-level clustering on the electronic properties of alloys.

### TARGETS FOR 2020

- Establish nanolayer-based passivation approaches for hexagonal silicon-germanium nanowires.
- Combine carefully matched transition metal chalcogenides into luminescent core-shell (hetero)structures.

## THEME 3.4 **Semiconductor Nanowires**

*Project leader: Erik Bakkers*

It has been a holy grail for several decades to demonstrate direct bandgap light emission in silicon [IYE93]. As a consequence, Si-photonics is lacking a Si-compatible light source. Here we study the light emission [FAD19] from hexagonal crystal phase SiGe, which can be fabricated [HAU15,HAU17] by growing a wurtzite GaAs nanowire core surrounded by a SiGe shell. In this growth method, the SiGe shell is forced into the hexagonal crystal phase. Hex-Ge is a direct bandgap semiconductor [ROD19] as shown in Figure 20a. Extrapolations between Hex-Si and Hex-Ge predict that Hex-SiGe will be a direct bandgap semiconductor at Ge-compositions above 65% as shown in Figure 20b.

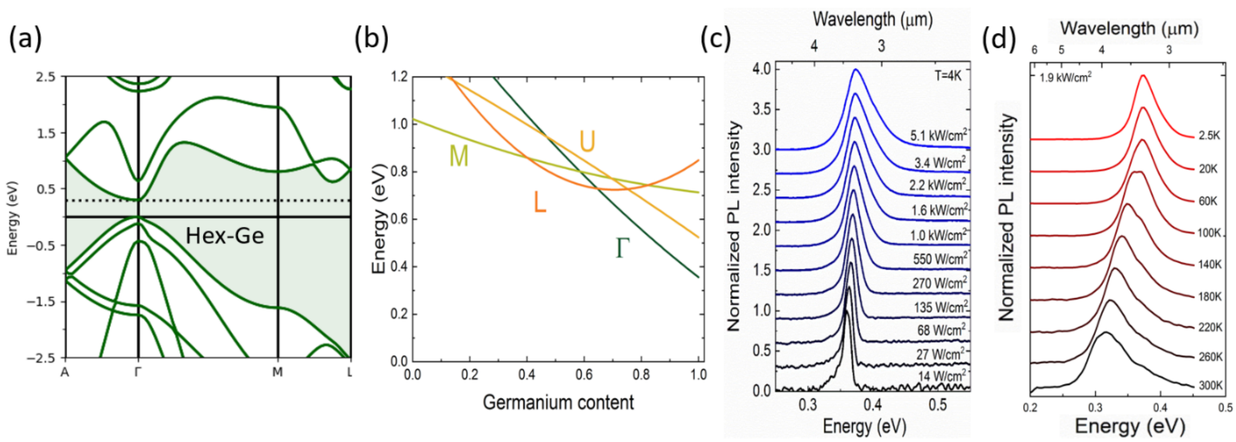



*Figure 20 (a) Calculated [ROD19] bandstructure of Hex-Ge. (b) Calculated band edges in Hex-SiGe showing that Hex-SiGe is a direct bandgap semiconductor above Ge-compositions of 65%. Measured photoluminescence versus excitation power (c) and versus temperature (d) of the photoluminescence spectrum of Hex-Ge.*

We measured the photoluminescence spectra of Hex-Ge as a function of excitation power and temperature as shown in Figure 20c,d. Importantly, the spectra can be interpreted as being exclusively due to band-to-band recombination, as evidence by the observation of Burstein-Moss bandfilling at high excitation and a Fermi Dirac tail at high temperature.

We subsequently measured the photoluminescence spectra of Hex-$Si_{1-X}Ge_X$ as a function of the composition as shown in Figure 21a. We observe a broad tunability of the direct bandgap between 1.8 µm at x=0.65 and 3.5 µm at x=1, measured at 4K. For serving as a light emitter in Si-photonics, the radiative efficiency at room temperature is most important. The radiative emission rate can be expressed as $R_{rad} = B_{rad} \cdot n \cdot p$ in which $n$ and $p$ are the electron and hole density and $B_{rad}$ is the coefficient for radiative recombination. A careful study revealed that the measured photoluminescence lifetime of 0.9 ns as displayed in Figure 21b is actually equal to the radiative lifetime at an activated donor density of ~$10^{19}cm^{-3}$. We thus obtain a $B_{rad} = \frac{1}{\tau_{rad} n_0} \sim 1.1 \cdot 10^{-10} cm^3/s$, which is almost equal to the $B_{rad}$ of InP.

The measurements of the optical properties clearly show that Hex-$Si_{1-x}Ge_x$ is a Si-compatible semiconductor with very similar properties as a III/V semiconductor. It even seems that Hex-$Si_{1-x}Ge_x$ outperforms conventional group III/V semiconductors since it features a temperature independent radiative efficiency between 4K and 300K at an excitation density of 30 kW/$cm^2$, as shown in Figure 21c.

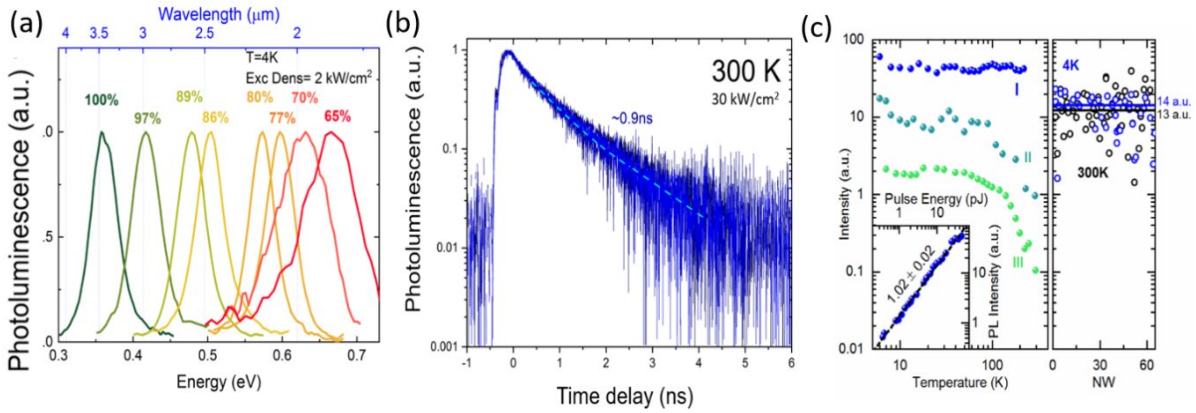



*Figure 21 (a) Tunability of the emission spectrum of Hex-$Si_{1-x}Ge_x$ at 4K. (b) Measured photoluminescence lifetime of Hex-$Si_{0.2}Ge_{0.8}$ at room temperature. (c) Temperature dependence of the photoluminescence intensity for 3 different classes on Hex-SiGe nanowires, showing a temperature-independent behavior for class I. The right panel shows a comparison between 60 individual nanowires at 4K and at 300K, showing almost identical emission intensity.*

Hex-$Si_{1-x}Ge_x$ is thus very promising for providing Si-photonics with a light emitter with a broad tunability. Possible applications include chip-to-chip communication, photonic networks on chip, infrared optical sensors and LiDAR using passive Si-photonics circuitry in combination with a Hex-SiGe light emitter.

For research on other aspects of Hex-$Si_{1-x}Ge_x$, see for example [ASS19, REN19]. This project has also received funding from the European Union’s Horizon 2020 research and innovation program under grant agreement No 735008 (SiLAS).

### TARGETS FOR 2020

- Demonstrate lasing in hexagonal SiGe.

# OUTREACH

## MEDIA COVERAGE OF GRAVITATION PROGRAM AND PEOPLE

Interview with Ton Backx on BNR Nieuwsradio in The Green Quest, broadcasted on 9 Sep 2019
https://thegreenquest.nl/green-gallery/2-itb2-datacenters/

Evening TV program "EenVandaag" on national channel NPO1, focussed on energy consumption of data centers, with interview to Ton Backx, Saturday February 8, 2020, 18.15.
https://www.npostart.nl/eenvandaag/08-02-2020/AT_2123890

Volkskrant 23 aug 2019 “Wifinetwerken slibben dicht. Hoe draadloos internet toch soepel en snel blijft” discusses 5G developments and lifi, and cites Ton Koonen.

## WIDE-AUDIENCE PRESENTATIONS

Patty Stabile, presentation on “Neuromorphic Computing” at the symposium organized in occasion of Peter Winzer honorary doctorate, Eindhoven, 5 June 2019.

Bert Koopmans, “Quantum & Relativity on the Chip – New routes for NanoElectronics”, Lecture for the 4th Young Brainport Summer School, Eindhoven, 12 August, 2019.

Ton Backx speaker at the Datacenter Innovations Day 19 september 2019, Utrecht (https://www.dutchdatacenters.nl/agenda/datacenter-innovations-day/)

Bert Koopmans, “Spannende nano-elektronica met Spinnende elektronen”, Masterclass for high school students, Van Maerlant Lyceum, Eindhoven, 12 September, 2019.

Ton Koonen, “Photonic Systems and Networks - state-of-the-art, outlook to the future,” Eindhoven Fiber Exchange 15 jarig bestaan, Eindhoven, 30 October, 2019

Ton Koonen, “Optical Wireless Communication - the benefits of fiber without needing a fiber,” Science Café Studium Generale, Eindhoven, 19 November, 2019

Andrea Fiore, lecture "Disruptive chips for light", Holst Symposium, Eindhoven, 21 November 2019

## DIRECT CONTACT WITH THE PUBLIC

The Dutch Design Week (DDW) is a yearly event in Eindhoven to present and promote Dutch design and innovation. In 2019, TU/e organized a special exhibit called “Drivers of Change”, showing forefront research and design. An important part of this exhibit were 8 demos on photonics and photonic integration. The exhibit was visited by approximately 17000 people in the week October 19-27, 2019.

List of photonics demos:

- **Operation of Light Guides** (Rob van der Heijden, Jaime Gomez Rivas, Gabriel Castellanos Gonzalez, Mohammad Ramezani);
- **Integrated Photonics** (Marija Trajkovic, Florian Lemaitre, Kevin Williams);
- **Faster Internet for 5G** (Bitao Pan, Eduardo Magalhaes, Fu Wang, Xuwei Xue, Nicola Calabretta);

- **Nanowire Solar Cells** (Jos Haverhorst, Ksenia Korzun, Ilya Kolpakov, Emanuele Bocchichio);
- **Optical Wireless Communication** (Ketemaw Mekonnen, Quan Pham, Zizheng Cao, Xuebing Zheng, Eduward Tangdiongga, Ton Koonen);
- **Photonic Integration for Sensors** (Anne Sauermann, Luca Picelli, Kaylee Hakkel, Gustav Lindgren, Rob van der Heijden, Andrea Fiore);
- **Seeing Nano Matter with the Naked Eye** (Gabriel Castellanos Gonzalez, Mohammad Ramezani, Jaime Gómez Rivas);
- **Smart Bed** (Henrie van den Boom, Sebastiaan Overeem, Merel van Gilst, Ton Koonen).

The IPI introduction video on integrated photonics(https://www.youtube.com/watch?v=nZKw4BZC5LI) was shown continuously in a projection room within the exhibit. Guided tours were provided throughout the week, with help of some of our postdocs and of the OSA student chapter. A number of presentations for the public were held during the week (by Marija Trajkovic, Ksenia Korzun, Andrea Fiore). A set of DDW-podcasts were made, one of which on photonics (https://soundcloud.com/user-246777937/episode-5-photonics).

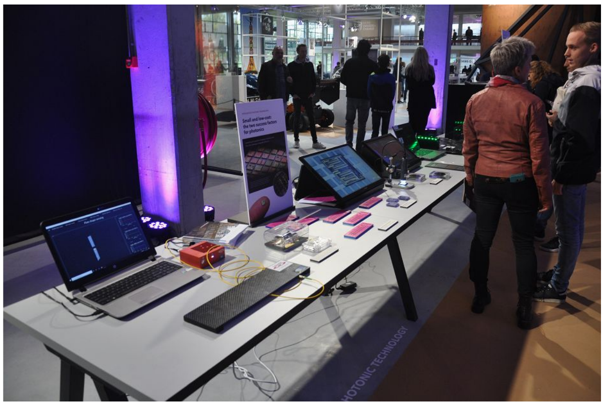


*Figure 22 Photos of the photonics exhibit at DDW2019*

# INSTITUTIONAL EMBEDDING AND ORGANISATIONAL STRUCTURE

## ORGANIZATIONAL AND MANAGEMENT STRUCTURE

The organizational structure of the program has remained approximately the same as last year (see Figure 23). Prof. Backx has stepped down from the position as Managing Director due to his retirement (January 2020). The Managing Director of the Faculties of Electrical Engineering and Physics, Jolie van Wevelingen, has replaced him as Managing Director of the program starting from May 1 2020.

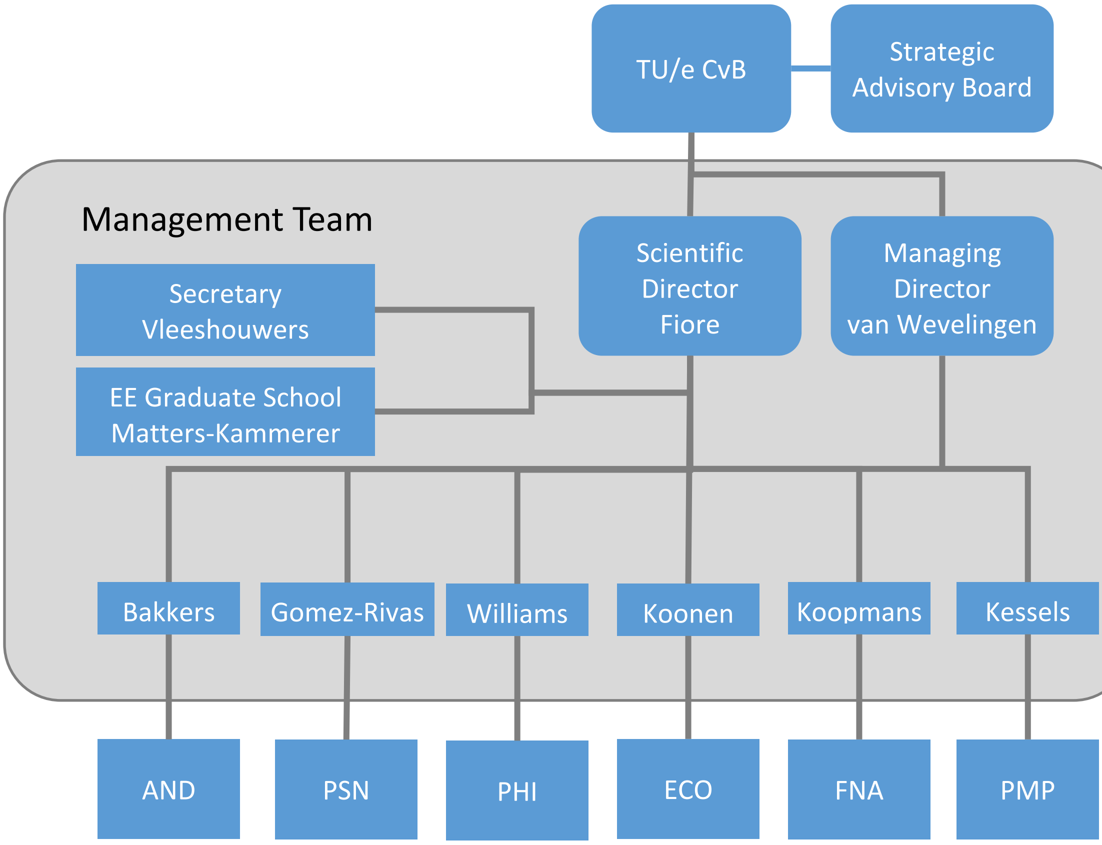



*Figure 23  Management Structure of the Research Centre for Integrated Nanophotonics as of May 1 2020*

Prof. Gomez-Rivas has become PSN group leader as of 1.10.2019. Prof. Marion Matters-Kammerer has taken over the position of Director of the Graduate Program within the EE department as of March 2020, and she will also fulfill this role within this program.

The Strategic Advisory Board has retained its composition:

- Prof. Rod Alferness (Dean of the College of Engineering, University of California Santa Barbara)
- Prof.dr.ir. Roel Baets (Photonics Research Group University of Gent, IMEC)
- Prof.dr. Polina Bayvel (Optical Communications and Networks University College London)

- Prof.dr.  Jonathan Finley (Semiconductor Quantum Nanosystems, Technische Universität München)
- Prof. Sailing He (Director Sino-Swedish Joint Research Center Photonics, ZheJiang University)
- Dr. Patrick de Jager (Senior Director Business Development ASML)
- Prof. Henning Riechert (Director Paul Drude Institut, Berlin until 31.12.19, thereafter participating on personal basis)

Management members are:

- Prof. Bart Smolders (Dean of the TU/e Faculty of Electrical Engineering)
- Prof. Gerrit Kroesen (Dean of the TU/e Faculty of Applied Physics)

Chairman of the committee is prof. Frank Baaijens, Rector of the TU/e. Secretary to the committee is dr.ir. Jan Vleeshouwers, who is also coordinator of the Gravitation program.

The groups involved in this program are expanding, with five new staff positions being created in the photonics area. The PhI group has completed the hiring a new full professor (**Martijn Heck**, presently at Aarhus Univ.), who has started in April 2020 and will be integrated in the activities of the Zwaartekracht program. The so-called Sectorplan has provided funding for three additional assistant professors in the area of photonics. An assistant professor, **Weiming Yao**, has been hired in the PhI group (started January 2020) and will be supported by the Gravitation program with one PhD position.

Improving the gender balance is a major goal of the SectorPlan program and an active search of female applicants has been realized at TU/e level. As assistant professor has been hired in the ECO group (**Joanne Oh**, started April 2020). An assistant-professor hiring on a photonics-related profile is under negotiation within the AND group and a selection is still ongoing for "Metaphotonics" position.

# EDUCATING AND ATTRACTING TALENT

Photonics is present in the TU/e education curriculum through a number of Bachelor and Master courses in both the Applied Physics (AP) and in Electrical Engineering (EE) departments.

New initiatives aimed at providing specific training programs in Photonics have recently been initiated by the members of this program, in collaboration with the Graduate Program Directors of the departments Applied Physics and Electrical Engineering.

A special subtrack in Photronics (integration of Electronics and Photonics), within the EE Master track Connected World Technologies is planned to start in 2020-21 (subject to modifications due to the ongoing Covid-19 crisis). The new Master track will provide the necessary training program for electronic-photonic co-design.

## ONLINE MICROMASTER IN PHOTONICS

A major new development is the initiative of an online MicroMaster in Photonics, proposed and coordinated by dr. Oded Raz. It will consist of three courses, given by teachers of the IPI groups, on different aspects of photonics: Fundamentals of photonics, Photonic integration and Photonic systems. The internal funding for this initiative has been secured and one course will be operational in the fall 2020, while two other courses will start in 2021. One of the goals of this online program is to increase the visibility of integrated photonics at TU/e and thereby the capacity to attract promising oversea students, for PhD positions as well as for the local photonics industry.

Besides, photonics is gradually taking a larger role in the Master programs of both departments. In particular, the Master in Applied Physics will have a new structure starting from academic year 2020-21, and photonics will be more visible in the *"Nano, Quantum and Photonics"* track. Two new photonics courses will be offered, an introductory *"Photonics"* course and a course *"Optical sensing and metrology"* jointly given by AP and EE teachers for the two departments.

## PHOTONDELTA FAST CAREER TRACK PROGRAM

A new initiative has been launched in 2019 to attract more Master students towards a photonics specialization: The *PhotonDelta Fast Career Track Program*. Starting AP and EE Master students are offered the possibility to participate to the activities of IPI and of the new student chapter (see below), coaching and assistance in finding internships abroad or in industry, and a direct contact with relevant photonics companies at the end of their studies. Students in the program are expected to attend two courses in photonics and do their final project in an IPI group. The initiative has been quite successful, with ~20 students enrolled, mostly from physics. The number of students looking for a photonics internship has increased very significantly. Efforts will be ramped up next year to make the program more popular among EE students.

## PHOTONICS SOCIETY EINDHOVEN

At the PhD level, the quarterly IPI/Gravitation quarterly events and the Annual Retreat feature talks from both guest speakers and internal PhD students, and poster sessions. They represent the main vehicle for broadening the scientific background of PhD students involved in the Gravitation program. The first Annual retreat took place in May 2019. An OSA Student Chapter *Photonics Society Eindhoven* has been founded in 2019 under the initiative of dr. Alberto Curto, and is organizing events (pizza lectures, visits to companies) targeted at PhD and Master students.


*Figure 24  Photos of the first event of the Student Chapter (November 2019)*

# PUBLICATION OUTPUT

In 2019 we published 152 papers on topics related to the Gravitation project, of which 87 were journal articles. 21 were joint publications (multiple groups participating to the program). The full list is provided in the Annex, the ones cited in this report are listed below together with publications which we consider particularly relevant. The publications in bold are considered key publications for this year. Patents are listed in the Utilisation section. External references are listed separately.

## THEME 1: PERVASIVE OPTICAL SYSTEMS

***Journal publications***

| | Publication | | |
|---|---|---|---|
| CAO19 | **Cao, Z., Zhang, X., Osnabrugge, G., Li, J., Vellekoop, I. M., & Koonen, A. M. J. (2019). *Reconfigurable beam system for non-line-of-sight free-space optical communication.* Light: Science and Applications, 8(1), [69].** https://doi.org/10.1038/s41377-019-0177-3 | ECO | 1.1 |
| | Cardarelli, S., Calabretta, N., D'Agostino, D., Stabile, R., & Williams, K. A. (2019). *Voltage-driven near field beam shifting in an InP photonic integrated circuit.* IEEE Journal of Quantum Electronics, 55(1), [8584479]. https://doi.org/10.1109/JQE.2018.2888849 | PHI, ECO | 1.1 |
| | Cardarelli, S., Calabretta, N., Stabile, R., & Williams, K. (2019). *Voltage-driven 1 × 2 multimode interference optical switch in InP/inGaAsP*. IET Optoelectronics, 13(6), 308-313. https://doi.org/10.1049/iet-opt.2018.5081 | PHI, ECO | 1.2, 1.3 |
| KOO19 | Koonen, A. M. J., Mekonnen, K. A., Huijskens, F. M., Cao, Z., & Tangdiongga, E. (2019). *Fully passive user localization for beam-steered high-capacity optical wireless communication system.* Manuscript submitted for publication. | ECO | 1.1 |
| KOO20 | Koonen, A. M. J., Mekonnen, K.A., Cao, Z., Huijskens, F., Pham, N. Q., Tangdiongga, E. (2020). *Ultra-high capacity wireless communication by means of steered narrow optical beams,* Philosophical Transactions A of the Royal Society, invited, March 2020, https://doi.org/10.1098/rsta.2019.0192 | ECO | 1.1 |
| RAZ20 | **Mohammed M.A., Melskens J., Stabile R., Pagliano F., Li C., Kessels W.M.M., Raz, O. (2020). *Metastable Refractive Index Manipulation in Hydrogenated Amorphous Silicon for Reconfigurable Photonics*. Advanced Optical Materials, 8, 1901680 (2020)** | ECO, PMP, PSN | 1.2 |
| ROM17 | Rommel, S. et al. (2017). *Few-mode fiber, splice and sdm component characterization by spatially-diverse optical vector network analysis,* Opt. Express 25, 22347–22361 (2017). | | |
| SHI20a | Shi, B., Calabretta, N. and Stabile, R. (2020) *Numerical simulation of an InP photonic integrated cross-connect for deep neural networks on chip*, Applied Sciences, 10 (2), 474, 2020. | ECO | 1.3 |
| WAN19 | Wang, Y., Engelen, J. P. van, Reniers, S., Rijn, M. B. J. van, Zhang, X., Cao, Z., Calzadilla, V., Williams, K.A., Smit, M. K., and Jiao Y. (2019). *InP-based grating antennas for high resolution optical beam steering*, IEEE Journal of Selected Topics in Quantum Electronics, pp. 1-1, 2019. https://doi.org/10.1109/JSTQE.2019.2958999 | PHI, ECO | 1.1, 2.1 |
| WEE19 | Weerdenburg, J. van, et al. (2019). *Enhanced Modal Dispersion Estimation Enabled by Chromatic Dispersion Compensation in Optical Vector Network Analysis,* in Journal of Lightwave Technology, vol. 37, no. 16, pp. 4001-4007, 15 Aug.15, 2019. | ECO | 1.4 |
| ZHA19a | Zhang, X., Li, C., Jiao, Y., Tangdiongga, E., Liu, Y., Cao, Z., & Koonen, T. (2019). *Crosstalk-mitigated AWGR-based two-dimensional IR beam-steered indoor optical wireless communication system with a high spatial resolution.* Journal of Lightwave Technology, 37(15), 3713-3720. [8718259]. https://doi.org/10.1109/JLT.2019.2917835 | PHI, ECO | 1.1 |

| | | | |
|---|---|---|---|
| ZHA19 | Zhang, X., van Engelen, J., Reniers, S., Cao, Z., Jiao, Y., & Koonen, A. M. J. (2019). *Reflecting AWG by using photonic crystal reflector on Indium-phosphide membrane on silicon platform.* IEEE Photonics Technology Letters, 31(13), 1041-1044. [8715809]. https://doi.org/10.1109/LPT.2019.2917147 | PHI, ECO | 1.1, 2.1 |

### *Keynotes & invited presentations*

| | Publication | | |
|---|---|---|---|
| | Bin Shi, Nicola Calabretta, Ripalta Stabile, *InP photonic circuit for deep neural networks*, Advanced Photonic Congress, Integrated Photonics Research, Silicon and Nanophotonics, San Francisco, CA, USA, 29 August-1 July 2019 | ECO | 1.3 |
| | Ton Koonen, *Fully passive user localisation for beam-steered high-capacity optical wireless communication system* (ECOC 2019), Dublin, Ireland, 22-24 September 2019 | ECO | 1.1 |
| KOO19a | Ton Koonen, *Recent advances in ultra-broadband optical wireless communication* (Asia Communications and Photonics Conference) Chengdu, China, 2-5 November 2019 | ECO | 1.1 |
| | Oded Raz, *Programmable Photonics* (Photon Delta Day), Amsterdam, The Netherlands December 2019. | ECO | 1.2 |
| | Ripalta Stabile, "Neural Networks on Chip through InP Photonic Integrated Cross-Connects", ERC International Workshop on Photonic Reservoir Computing and Information Processing in Complex Network, Trento, 4-6 December 2019, | ECO | 1.4 |

### *Conference publications*

| | Publication | | |
|---|---|---|---|
| DAG15 | D'Agostino, D., et. al. (2015). *Widely tunable Coupled Cavity Laser based on a Michelson Interferometer with doubled Free Spectral Range*, in Optical Fiber Communication Conference, 2015, p. M2D.4. | ECO, PHI | 1.3 |
| HEI19 | Heide, S. van der, Chen, B., Hout, M. van den, Liga, G., Koonen, T., Hafermann, H., ... Okonkwo, C. (2019). *11,700 km transmission at 4.8 bit/4D-sym via four-dimensional geometrically-shaped polarization-ring-switching mModulation.* In OECC/PSC 2019 - 24th OptoElectronics and Communications Conference/International Conference Photonics in Switching and Computing 2019 [8817687] Piscataway: Institute of Electrical and Electronics Engineers. https://doi.org/10.23919/PS.2019.8817687 | ECO | 1.4 |
| | Morant, M., Trinidad, A. M., Tangdiongga, E., & Llorente, R. (2019). *Multi-core fiber technology supporting MIMO and photonic beamforming in 5G multi-antenna systems: (Invited paper).* In 2019 IEEE International Topical Meeting on Microwave Photonics, MWP 2019 [8892041] Piscataway: Institute of Electrical and Electronics Engineers. https://doi.org/10.1109/MWP.2019.8892041 | ECO | 1.1 |
| PHA19 | Pham, N., Mekonnen, K. A., Tangdiongga, E., Mefleh, A., & Koonen, A. M. J. T. (2019). *Accurate indoor localization for beam-steered OWC system using optical camera.* In Proceedings of the 45th European Conference on Optical Communication (ECOC 2019) [P45] Institution of Engineering and Technology (IET). | ECO | 1.1 |
| SHI19 | Shi, B., Calabretta, N., & Stabile, R. (2019). *First demonstration of a two-layer all-optical neural network by using photonic integrated chips and SOAs.* Paper presented at The 45th European Conference on Optical Communication, Dublin, Ireland. | ECO | 1.3 |
| SHI20 | Shi, B., Calabretta, N. and Stabile, R. (2020). *Lossless monolithically integrated photonics InP neuron for all-optical computation*, OFC 2020. | ECO | 1.3 |

| | | | |
|---|---|---|---|
| TRI19 | Trinidad, A., Tessema, N., Cao, Z., Zantvoort, J. van, Tangdiongga, E., Koonen, T. (2019). *Broadband Photonic Integrated Multi-RF Beamformer For K-Band Applications,* ECOC 2019, 15-19 Sep. 2019, Dublin, Ireland, paper M2.B.3 | ECO | 1.1 |
| | Xue, X., Prifti, K., Wang, F., Yan, F., Pan, B., Guo, X., & Calabretta, N. (2019). *Experimental assessment of photonic integrated switches based optical data center networks with virtual network slice services (Invited)*. In ICOCN 2019 | ECO | 1.2 |

# THEME 2: NANOPHOTONIC INTEGRATED CIRCUITS

***Journal publications***

| | Publication | | |
|---|---|---|---|
| JIA19 | Jiao, Y., Tol, J. van der, Pogoretskii, V., Engelen, J. van, Kashi, A. A., Reniers, S., Wang, Y., Zhao, X., Yao, W., Liu, T., Pagliano, F., Fiore, A., Zhang, X., Cao, Z., Kumar, R. R., Tsang, H. K., Veldhoven, R. van, Vries, T. de, Geluk, E.-J., Bolk, J., Ambrosius, H., Smit, M., and Williams, K. (2019). *Indium Phosphide Membrane Nanophotonic Integrated Circuits on Silicon*, Physica Status Solidi (a), p. 1900606, 2019. | PHI, PSN | 2.1 |
| KHA19 | Khatibi, A., Godiksen, R.H., Basuvalingam, S.B., Pellegrino, D., Bol, A.A., Shokri, B. and Curto, A. G. (2020). *Anisotropic infrared light emission from quasi-1D layered TiS3*. 2D Matter. 7, 015022 (2020) DOI: 10.1088/2053-1583/ab57ef | PSN, PMP | 2.2 |
| KUM19 | Kumar, R. R., Raevskaia, M., Pogoretskii, V., Jiao, Y., and Tsang, H. K. (2019). *Entangled photon pair generation from an InP membrane micro-ring resonator*, Applied Physics Letters, vol. 114, p. 021104, 2019. https://doi.org/10.1063/1.5080397 | PHI | 2.1 |
| KUM19a | Kumar, R. R., Raevskaia, M., Pogoretskii, V., Jiao, Y., and Tsang, H. K. (2019). *InP membrane micro-ring resonator for generating heralded single photons,* Journal of Optics, vol. 21, p. 115201, 2019. | PHI | 2.1 |
| LIU19 | Liu T., Pagliano, F., Veldhoven, R.P. van, Pogoretskiy, V., Jiao, Y. and Fiore, A., *Integrated Nano-Opto-Mechanical Displacement Sensor with Ultrawide Optical Bandwidth*, to be published in Nature Comm. | PSN, PHI | 2.2 |
| | Liu, T., Pagliano, F., van Veldhoven, R., Pogoretskiy, V., Jiao, Y., & Fiore, A. (2019). *Low-voltage MEMS optical phase modulators and switches on a indium phosphide membrane on silicon.* Applied Physics Letters, 115(25), [251104]. https://doi.org/10.1063/1.5128212 | PSN, PHI | 2.2 |
| REN19 | Reniers, S. F. G., Wang, Y., Williams, K. A., Tol, J. J. G. M. van der, and Jiao Y. (2019). *Characterization of Waveguide Photonic Crystal Reflectors on Indium Phosphide Membranes*, IEEE Journal of Quantum Electronics, vol. 55, pp. 1-7, 2019. https://doi.org/10.1109/JQE.2019.2941578 | PHI | 2.1 |
| TOL20 | Tol, J. J. G. M. v. d., Jiao, Y., Engelen, J. P. van, Pogoretskiy, V., Kashi, A. A., and Williams, K. (2020). *InP Membrane on Silicon (IMOS) Photonics*, IEEE Journal of Quantum Electronics, vol. 56, pp. 1-7, 2020. | PHI | 2.1 |
| WAN19 | Wang, Y., Engelen, J. P. van, Reniers, S., Rijn, M. B. J. van, Zhang, X., Cao, Z., Calzadilla, V., Williams, K., Smit, M. K., and Jiao, Y. (2019). *InP-based grating antennas for high resolution optical beam steering*, IEEE Journal of Selected Topics in Quantum Electronics, pp. 1-1, 2019. https://doi.org/10.1109/JSTQE.2019.2958999 | PHI, ECO | 1.1, 2.1 |
| ZHA19 | Zhang, X., Engelen, J. van, Reniers, S., Cao, Z., Jiao, Y., and Koonen, A. M. J. (2019). *Reflecting AWG by Using Photonic Crystal Reflector on Indium-Phosphide Membrane on Silicon Platform*, IEEE Photonics Technology Letters, vol. 31, pp. 1041-1044, 2019. https://doi.org/10.1109/LPT.2019.2917147 | PHI, ECO | 1.1, 2.1 |

### ***Keynotes & invited presentations***

| | Publication | | |
|---|---|---|---|
| | Meint Smit, *Integration of Photonics and Electronics*: ISSCC 2019 - International Solid-State Circuits Conference, 17-21 February 2019, San Francisco USA. | PHI | 2.1 |
| | Andrea Fiore et al., *Purcell enhancement in practical nanoLEDs and nanolasers* (SPIE Photonics West), San Francisco, United States, 2-7 February 2019 | PSN | 2.2 |
| | Kevin Williams, *Indium Phosphide Membrane Photonics on Silicon*: Optical Fiber Communication Conference (OFC 2019), San Diego, California United States, 3–7 March 2019. | PHI | 2.1 |
| | Jos van der Tol, *InP Membrane on Silicon (IMOS) Photonics*: the 21th European Conference on Integrated Optics (ECIO 2019), 24-26 April 2019, Ghent, Belgium. | PHI | 2.1 |
| | Alberto G. Curto, *Enhancing valley-polarized light emission from 2D semiconductors*: POEM2019 - 2nd Photonic and Optoelectronic Materials Conference. 9-12 April 2019, London, UK | PSN | 2.2 |
| | Yuqing Jiao, *InP membrane lasers and active-passive integration*: Compound Semiconductor Week (CSW 2019), 19-23 May 2019, Nara, Japan. | PHI | 2.1 |
| | Jos van der Tol, *Low-cost and high-speed nanophotonic integrated circuits for access networks*: IEEE Summer Topical Meeting 2019, 8-10 July 2019, Fort Lauderdale, Florida, USA. | PHI | 2.1 |
| | Alberto G. Curto, *Chiral nanophotonics with 2D semiconductors*: METANANO 2019 – International Conference on Metamaterials and Nanophotonics.15-19 July 2019, Saint Petersburg, Russia | PSN | 2.2 |
| | Andrea Fiore et al., *Nano-opto-electro-mechanical systems for optical switching and sensing* (META 2019), Lisbon, Portugal 23-26 July 2019 | PSN | 2.2 |
| | Yuqing Jiao, *Novel photonic integrated devices on a double-sided InP membrane*: SPIE/COS Photonics Asia, 20-23 October 2019, Hangzhou, China. | PHI | 2.2 |
| | Yuqing Jiao, *IMOS Integrated Photonics for Free-space Sensing and Communications*: Asia Communications and Photonics Conference (ACP 2019), 2-5 November 2019, Chengdu, China. | PHI | 2.2 |

### ***Conference publications***

| | Publication | | |
|---|---|---|---|
| ENG19 | Engelen, J. van, Reniers, S., Bolk, J., Williams, K., Tol, J. van der, and Jiao, Y. (2019). *Low Loss InP Membrane Photonic Integrated Circuits Enabled by 193-nm Deep UV Lithography*, in the Compound Semiconductor Week (CSW 2019), 19-23 May 2019, Nara, Japan. Paper MoA3-7. https://doi.org/10.1109/ICIPRM.2019.8819069 | PHI | 2.1 |
| ENG19a | Engelen, J.P. van, Bolk, J., Zhang, X., Williams, K.A., Jiao, Y., Tol, J.J.G.M. van der. (2019). *Arrayed waveguide grating in InP membrane on silicon patterned by 193-nm deep UV lithography*, in the Proceedings of the 24th Annual Symposium of the IEEE Photonics Society Benelux Chapter, 21-22 November 2019, Vrije Universiteit, Amsterdam, The Netherlands. | PHI | 2.1 |

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|---|---|---|---|
| **JIA19a** | Jiao, Y., Pogoretskii, V., Engelen, J. van, Kelly, N., Tol, J. van der. (2019). *InP membrane lasers and active-passive integration*, in the Compound Semiconductor Week (CSW 2019), 19-23 May 2019, Nara, Japan. Invited Paper TuA3-7. https://doi.org/10.1109/ICIPRM.2019.8819210 | PHI | 2.1 |
| **JIA19b** | Jiao, Y., Tol, J. van der, Yao, W., Williams, K. (2019) *Low-cost and high-speed nanophotonic integrated circuits for access networks*, in the IEEE Summer Topical Meeting 2019, 8-10 July 2019, Fort Lauderdale, Florida, USA. Invited Paper TuB4.2. https://doi.org/10.1109/PHOSST.2019.8794949 | PHI | 2.1 |
| **JIA19c** | Jiao, Y., *Novel photonic integrated devices on a double-sided InP membrane*, in the SPIE/COS Photonics Asia, 20-23 October 2019, Hangzhou, China. Invited paper 11184-24. | PHI | 2.1 |
| **JIA19d** | Jiao, Y., Kashi, A.A., Wang, Y., Pogoretskiy, V., Williams, K. (2019). *IMOS Integrated Photonics for Free-space Sensing and Communications*, in the Asia Communications and Photonics Conference (ACP 2019), 2-5 November 2019, Chengdu, China. Invited paper T3D.1. | PHI | 2.1 |
| | Liu, T., Pagliano, F., van Veldhoven, R., Pogoretskii, V., Jiao, Y., & Fiore, A. (2019). *InP MEMS Mach-Zehnder interferometer optical switch on silicon.* In 2019 Conference on Lasers and Electro-Optics Europe and European Quantum Electronics Conference, CLEO/Europe-EQEC 2019 [8872336] Piscataway: Institute of Electrical and Electronics Engineers. https://doi.org/10.1109/CLEOE-EQEC.2019.8872336 | PSN, PHI | 2.2 |
| **TOL19** | Tol, J. van der, Jiao, Y., Engelen, J. van, Pogoretskiy, V., Kashi, A., and Williams, K. (2019). *InP Membrane on Silicon (IMOS) Photonics*, in the 21th European Conference on Integrated Optics (ECIO 2019), 24-26 April 2019, Ghent, Belgium. Invited paper T.A2.1. | PHI | 2.1 |
| | Wang, Y., van Engelen, J. P., Reniers, S., Rijn, M. van, Zhang, X., Cao, Z., ... Jiao, Y. (2019). *High resolution grating antennas for beam steering on the IMOS platform.* In Proceedings Asia Communications and Photonics Conference (ACPC) 2019 [M4B.5] OSA Publishing. | PHI, ECO | 1.1, 2.1 |
| **WIL19** | Williams, K.A., Pogoretskiy, V., Engelen, J.P. van, Kelly, N.P., Tol, J.J.G.M. van der, and Jiao, Y. (2019). *Indium Phosphide Membrane Photonics on Silicon*, in Optical Fiber Communication Conference (OFC) 2019, San Diego, California United States, 3–7 March 2019, paper M2D.4. | PHI | 2.1 |

## THEME 3: ULTIMATE CONTROL OF MATTER AND PHOTONS

### ***Journal publications***

| | Publication | | |
|---|---|---|---|
| **ASS19** | Assali, S., Albani, M., Bergamaschini, R., Verheijen, M. A., Li, A., Kölling, S., ... Miglio, L. (2019). *Strain engineering in Ge/GeSn core/shell nanowires.* Applied Physics Letters, 115(11), [113102]. https://doi.org/10.1063/1.5111872 | PSN, PMP, AND | 3.3, 3.4 |
| | Badawy, G., Gazibegovic, S., Borsoi, F., Heedt, S., Wang, C. A., Koelling, S., ... Bakkers, E. P. A. M. (2019). *High mobility stemless InSb nanowires*. Nano Letters, 19(6), 3575-3582. https://doi.org/10.1021/acs.nanolett.9b00545 | PSN, PMP, AND | 3.3, 3.4 |
| | Basuvalingam, S., Zhang, Y., Bloodgood, M., Godiksen, R. H., González Curto, A., Hofmann, J. P., ... Bol, A. (2019). *Low temperature phase-controlled synthesis of titanium di- and tri-sulfide by atomic layer deposition.* Chemistry of Materials, 31(22), 9354-9362. https://doi.org/10.1021/acs.chemmater.9b02895 | PSN, PMP | 3.3 |
| **BEE19a** | Beens, M., Lalieu, M. L. M., Deenen, A. J. M., Duine, R. A., & Koopmans, B. (2019). *Comparing all-optical switching in synthetic-ferrimagnetic multilayers and alloys.* Physical Review B, 100(22), [220409(R)]. https://doi.org/10.1103/PhysRevB.100.220409 | FNA | 1.3, 3.2 |

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|---|---|---|---|
| BEE19b | Beens, M., Lalieu, M. L. M., Duine, R. A., & Koopmans, B. (2019). *The role of intermixing in all-optical switching of synthetic-ferrimagnetic multilayers.* AIP Advances, 9(12), [125133]. https://doi.org/10.1063/1.5129892 | FNA | 1.3, 3.2 |
| BLA17 | Black, L. E., Cavalli, A., Verheijen, M. A., Haverkort, J. E. M., Bakkers, E. P. A. M., Kessels, W. M. M. (2017). *Effective Surface Passivation of InP Nanowires by Atomic-Layer-Deposited $Al_2O_3$ with $PO_x$ Interlayer*, Nanoletters 2017, 17, 6287-6294. | PMP | 3.3 |
| CAS19 | Castellanos, G.W., Bai, P., and Gomez Rivas, J. (2019). *Lattice resonances in dielectric metasurfaces.* Journal of Applied Physics 125 (21), 213105. DOI: 10.1063/1.5094122 | PSN | 3.1 |
| CAS20 | Castellanos, G.W., Murai, S., Raziman, T. V., Wang, S., Ramezani, M., Curto, A.G., and Gómez Rivas, J. (2020). *Exciton-Polaritons with Magnetic and Electric Character in All-dielectric Metasurfaces.* Under review. | PSN | 3.1 |
| FAD20 | Fadaly, E.M.T. et al. (2020). *Direct Band Gap Emission from Hexagonal Ge and SiGe Alloys*. Nature 580, 205 (2020). | AND, PSN | 3.4 |
| | Gazibegovic, S., Badawy, G., Buckers, T. L. J., Leubner, P., Shen, J., de Vries, F. K., ... Bakkers, E. P. A. M. (2019). *Bottom-up grown 2D InSb nanostructures.* Advanced Materials, 31(14), [1808181]. https://doi.org/10.1002/adma.201808181 | PSN, PMP, AND | 3.3, 3.4 |
| | Gibson, S. J., van Kasteren, B., Tekcan, B., Cui, Y., van Dam, D., Haverkort, J. E. M., ... Reimer, M. E. (2019). *Tapered InP nanowire arrays for efficient broadband high-speed single-photon detection.* Nature Nanotechnology, 14(5), 473-479. https://doi.org/10.1038/s41565-019-0393-2 | PSN, AND | 3.1, 3.4 |
| HEE20 | Hees, Y.L.W. van, Meugheuvel, P. van de, Koopmans, B., Lavrijsen, R. (2020). *Deterministic all-optical magnetization writing facilitated by non-local transfer of spin angular momentum*. Submitted, arXiv 2001.09033 (2020) | FNA | 3.2 |
| | Hoof, N. J. J. van, Huurne, S. E. T. ter, Vervuurt, R. H. J., Bol, A. A., Halpin, A., & Rivas, J. G. (2019). *Diffraction enhanced transparency in a hybrid gold-graphene THz metasurface.* APL Photonics, 4(3), [036104]. https://doi.org/10.1063/1.5080390 | PSN, PMP | 3.1 |
| KOO18a | Koopmans B., Y.L.W. van Hees, M.L.M. Lalieu, F.E. Demirer, J.J.G.M. van der Tol and R. Lavrijsen, *Towards Integrated MagnetoPhotonics using Claddings with Perpendicular Magnetic Anisotropy*. ECIO 2018, IEEE (2018). | FNA, PHI | 3.2 |
| LAL17 | Lalieu M. L. M., Peeters, M. J. G., Haenen, S. R. R., Lavrijsen, R. and Koopmans, B. (2017). *Deterministic all-optical switching of synthetic ferrimagnets using single femtosecond laser pulses*. Phys. Rev. B 96, 220411(R) (2017). | FNA | 3.2 |
| LAL19 | Lalieu, M. L. M., Lavrijsen, R., & Koopmans, B. (2019). *Integrating all-optical switching with spintronics.* Nature Communications, 10(1), [110]. https://doi.org/10.1038/s41467-018-08062-4 | FNA | 1.3, 3.2 |
| | Lee, J. S., Choi, S., Pendharkar, M., Pennachio, D. J., Markman, B., Seas, M., ... Palmstrøm, C. J. (2019). *Selective-area chemical beam epitaxy of in-plane InAs one-dimensional channels grown on InP(001), InP(111)B, and InP(011) surfaces.* Physical Review Materials, 3(8), [084606]. https://doi.org/10.1103/PhysRevMaterials.3.084606 | PSN, PMP, AND | 2.1, 3.3 |
| | Le-Van, Q., Zoethout, E., Geluk, E. J., Ramezani, M., Berghuis, M., & Gómez Rivas, J. (2019). *Enhanced quality factors of surface lattice resonances in plasmonic arrays of nanoparticles.* Advanced Optical Materials, 7(6), [1801451]. https://doi.org/10.1002/adom.201801451 | PSN, PHI | 3.1 |
| | De Luca, M., Fasolato, C., Verheijen, M. A., Ren, Y., Swinkels, M. Y., Kölling, S., ... Zardo, I. (2019). *Phonon engineering in twinning superlattice nanowires.* Nano Letters, 19(7), 4702-4711. https://doi.org/10.1021/acs.nanolett.9b01775 | PSN, PMP, AND | 3.3, 3.4 |
| | Lucassen, J., Schippers, C. F., Verheijen, M. A., Fritsch, P., Geluk, E. J., Barcones, B., ... Lavrijsen, R. (2019). *Extraction of Dzyaloshinksii-Moriya interaction from propagating spin waves validated.* arXiv, [1909.02467v1]. | PMP, PHI, FNA | 3.2 |
| | Meijer, M. J., Lucassen, J., Fabian, K., Frömter, R., Kurnosikov, O., Duine, R. A., ... Lavrijsen, R. (2019). *Magnetic chirality controlled by the interlayer exchange interaction.* arXiv, [1909.08909v1]. | FNA | 3.2 |

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|---|---|---|---|
| MUR20 | Murai, S., Castellanos, G.W., Raziman, T. V., Curto, A.G., and Gómez Rivas, J. (2020). *Enhanced light emission by magnetic and electric resonances in dielectric metasurfaces*. arXiv:2003.05076 | PSN | 3.1 |
| REN19 | Ren, Y., Leubner, P., Verheijen, M., Haverkort, J., & Bakkers, E. (2019). *Hexagonal silicon grown from higher order silanes.* Nanotechnology, 30(29), [295602]. https://doi.org/10.1088/1361-6528/ab0d46 | PMP, AND | 3.3, 3.4 |

### *Keynotes & invited presentations*

| | Publication | | |
|---|---|---|---|
| | Erik Bakkers, '*Towards a photonic band edge laser using hexagonal-SiGe nanowire arrays*', plenary talk at SPIE, San Francisco, February 2020 | AND | 3.4 |
| | Erik Bakkers, '*Bottom-Up Grown Nanowire Quantum Devices*', plenary talk at Compound Semiconductor Week, Nara (Japan), May 2019 | AND | 3.4 |
| | Erik Bakkers, '*Hexagonal SiGe: Growth and Direct Bandgap Emission*', invited talk at ICCGE, Colorado, July 2019 | AND | 3.4 |
| | Erik Bakkers, '*Bottom-Up Grown Nanowire Quantum Devices*', invited talk at MRS, Phoenix, April 2019 | AND | 3.4 |
| | Erwin Kessels, '*Plasma Deposition and Plasma-Enhanced Atomic Layer Deposition*', invited talk at 66th Int. Symposium AVS Science & Technology Society, Columbus OH, U.S.A., October 2019 | PMP | 3.3 |
| | Erwin Kessels, '*Atomic layer deposition: recent developments and new insights*', invited talk at XII International Conference on Surface, Materials and Vacuum, San Luis Potosi, Mexico, September 2019 | PMP | 3.3 |
| | Erwin Kessels, '*Atomic Scale Processing: From Understanding to Innovation*', ALD Innovation Awardee Lecture at 19th International Conference on Atomic Layer Deposition, Bellevue WA, USA, July 2019 | PMP | 3.3 |
| | Erwin Kessels, '*Plasma-Based Selective Atomic Layer Deposition and Etching to Enable 5nm and Beyond Device Technology*', invited talk at 2019 Symposia on VLSI Technology and Circuits, Kyoto, Japan, June 2019 | PMP | 3.3 |
| | Erwin Kessels, '*Plasma-based ALD and ALE for selective deposition*', invited talk at Plasma Etch and Strip in Microelectronics, Grenoble, France, May 2019 | PMP | 3.3 |
| | Erwin Kessels, '*Atomic Layer Deposition Process Development*', invited talk at ALD for Industry – 3rd Workshop and Tutorial, Berlin, Germany, March 2019 | PMP | 3.3 |
| | Erwin Kessels, '*Atomically Engineered Materials and Processing*', invited talk at 7th Sungkyunkwan University Workshop on Materials Frontier Research, Seoul, Korea, January 2019 | PMP | 3.3 |
| | Stan ter Huurne, '*THz Resonances with Infinite Lifetime in Array of Gold Resonators*', Keynote presentation at IRMMW-THz 2019 – Paris, 3 Sep 2019 | PSN | 3.1 |
| | Jaime Gómez Rivas, '*Integrated Photonics Research, Silicon and Nanophotonics Extended open cavities for polaritonic devices*', invited talk at OSA Advanced Photonics Congress, San Francisco, USA, 2019-07-31/08-02 | PSN | 3.1 |
| | Jaime Gómez Rivas, '*THz resonances with arbitrary lifetime in metals and semiconductors*', invited lecture at PETER (Plasmon Enhanced Terahertz Electron Paramagnetic Resonance) workshop (Kleinwalsertal, Austria), June 2019 | PSN | 3.1 |

| | | | |
|---|---|---|---|
| | Jaime Gómez Rivas, '*Plasmon-exciton-polariton condensation and lasing*', keynote presentation at Optics, Photonics & Laser Technologies-2019, San Francisco, June 2019 | PSN | 3.1 |
| | Jaime Gómez Rivas, '*THz Resonances with Infinity Lifetime*', invited talk at POEM2019 - 2nd Photonic and Optoelectronic Materials Conference, University College London, London, April 2019 | PSN | 3.1 |
| | Jaime Gómez Rivas, '*Plasmon-exciton-polariton condensation and lasing*', invited talk at POEM2019 - 2nd Photonic and Optoelectronic Materials Conference, University College London, London, April 2019 | PSN | 3.1 |

***Conference publications***

As most contributed conference publications are not uploaded by the physics groups in the TU/e database, the list is not provided here.

***Other:***

| | Publication | | |
|---|---|---|---|
| BOM20 | Bomen, C. van den (2020). *Magnetic waveguide claddings,* MSc. Thesis 2020. | FNA | 3.2 |
| VOS19 | Vos, M. F. J., *Development and understanding of advanced atomic layer processes: $AlF_3$, Co and Ru*, PhD dissertation, Eindhoven University of Technology, November 2019 | PMP | 3.3 |

***External references cited in the report:***


FON13 Fontaine, N. K. et al. (2013). *Characterization of space-division multiplexing systems using a swept-wavelength interferometer,* OFC (2013)

MOU19 Mourgias-Alexandris, G., et al. (2019). *An all-optical neuron with sigmoid activation function*, Opt. Express, 27 (7), 2019

SHA18 Shastri, B. J., et al. (2018). *Principles of Neuromorphic Photonics*, Unconventional Computing, New York, NY: Springer US, 2018, 83–118.

SHE17 Shen, Y., et al. (2017) *Deep learning with coherent nanophotonic circuits,* Nat. Photonics, 11 (7), 441-446, 2017.

VEL 18 Velázquez-Benítez, A. M., et al. (2018). *Scaling photonic lanterns for space-division multiplexing,* Sci. reports 8, 8897(2018).

HAU15 Hauge, H. I. T. et al. (2015). *Hexagonal Silicon Realized.* Nano Lett. 15, 5855–5860.

HAU17 Hauge, I. T., et al. (2017). *Single-Crystalline Hexagonal Silicon − Germanium*. Nano Lett 17, 85–90.

IYE93 S. S. Iyer and Y.-H. Xie. (1993). *Light Emission from Silicon*. Science. 260, 40–46.

ROD19 Rödl, C. et al. *Accurate electronic and optical properties of hexagonal germanium for optoelectronic applications*. (2019). Phys.Rev.Materials 3, 034602.

# GLOSSARY

| | |
|---|---|
| 5G | 5th Generation Wireless Mobile systems, operating in the mm-wave range, intended to provide performance up to 10 times that of the 4G-network |
| ALD | Atomic Layer Deposition |
| AND | Consortium group: Advanced Nanomaterials and Devices |
| AOS | All-Optical Switching |
| ASD | Area-Selective Deposition |
| AWGR | Arrayed Waveguide Grating Router |
| BIC | Bound state in the Continuum |
| BiCMOS | Bipolar CMOS |
| BROWSE | Beam-steered Reconfigurable Optical-Wireless System for Energy-efficient communication (https://cordis.europa.eu/project/rcn/103158_en.html) |
| CMOS | Complementary Metal Oxide Semiconductor: most common Si-based technology for fabricating integrated circuits |
| CVD | Chemical Vapor Deposition |
| DUV | Deep Ultraviolet |
| DWDM | Dense Wave Division Multiplexing |
| ECO | Consortium group: Electro-Optical Communication |
| EO-polymer | Electro-Optic polymer |
| ERC | European Research Council (https://erc.europa.eu/) |
| f, femto | $10^{-15}$ |
| FCA | Free-Carrier Absorption |
| FNA | Consortium group: Physics of Nanosctructures |
| IMOS | InP Membrane On Silicon: a technique to integrate InP-based photonic circuitry with Si-based electronics |
| IPI | Institute for Photonic Integration |
| IR | Infrared |
| LED | Light-Emitting Diode |
| LIDAR | Light Detection And Ranging |
| LTE-A | Long Term Evolution is a standard for mobile communication which also defines frequency bands, such as the LTE-A band |
| MDL | Mode-Dependent Loss |
| MEMS | Micro Electromechanical Switch |
| MOKE | Magneto-Optic Kerr Effect |
| MPW | Multi-Platform Wafer |
| MZI, MZM | Mach-Zehnder Interferometer, Modulator |
| OFDM | Orthogonal Frequency Division Multiplexing |
| OVNA | Optical Vector Network Analyzer |
| OWC | Optical Wireless Communication |
| p, pico | $10^{-12}$ |
| PAM | Pulse Amplitude Modulation: PAM4 uses four pulse amplitude levels |
| PDL | Polarization-Dependent Loss |
| PhC | Photonic Crystal |
| PHI | Consortium group: Photonic Integration |
| PI | Principle Investigator |
| PIC | Photonic Integrated Circuit |
| PITC | Photonic Integration Technology Center |
| PL | Photo-luminescence |
| PMP | Consortium group: Plasma Materials and Processing |

| | |
|---|---|
| POF | Plastic Optical Fibre |
| PON | Passive Optical Network |
| PRA | Pencil Radiating Antenna |
| PSN | Consortium group: Photonics and Semiconductor Nanophysics |
| QAM | Quadrature Amplitude Modulation: modulates amplitude of two orthogonal carriers |
| RF | Radio Frequency |
| RF-OAM | Radio-Frequency Orbital Angular Momentum |
| SEM | Scanning Electron Microscopy (combined with TEM into STEM) |
| SLM | Spatial Light Modulator |
| SOA | Semiconductor Optical Amplifier |
| SOA-WC | SOA Wavelength Converter |
| TEM | Transmission Electron Microscopy (combined with SEM into STEM) |
| TL | Tunable Coupled-Cavity Laser |
| TRL | Technology Readiness Level |
| UV | Ultraviolet |
| VCSEL | Vertical Cavity Surface Emitting Laser |
| XT | Crosstalk |

# ANNEX: COMPLETE PUBLICATION LIST

(sorted by theme, than by first author)

| Title | Groups | Theme | Journ. (J) /Conf. (C) |
|---|---|---|---|
| Cao, Z., Zhang, X., Osnabrugge, G., Li, J., Vellekoop, I. M., & Koonen, A. M. J. (2019). Reconfigurable beam system for non-line-of-sight free-space optical communication. Light: Science and Applications, 8(1), [69]. https://doi.org/10.1038/s41377-019-0177-3 | ECO | 1.1 | J |
| Cardarelli, S., Calabretta, N., Koelling, S., Stabile, R., & Williams, K. (2019). Electro-optic device in InP for wide angle of arrival detection in optical wireless communication. In 2019 Optical Fiber Communications Conference and Exhibition, OFC 2019 - Proceedings [8696527] Institute of Electrical and Electronics Engineers. https://doi.org/10.1364/OFC.2019.Th1F.6 | PSN, PHI, ECO | 1.1 | C |
| Cardarelli, S., Calabretta, N., D'Agostino, D., Stabile, R., & Williams, K. A. (2019). Voltage-driven near field beam shifting in an InP photonic integrated circuit. IEEE Journal of Quantum Electronics, 55(1), [8584479]. https://doi.org/10.1109/JQE.2018.2888849 | PHI, ECO | 1.1 | J |
| Jungnickel, V., Hinrichs, M., Bober, K. L., Kottke, C., Corici, A. A., Emmelmann, M., ... Koonen, A. M. J. (2019). Enhance lighting for the internet of things. In 2019 Global LIFI Congress, GLC 2019 [8864126] Piscataway: Institute of Electrical and Electronics Engineers. https://doi.org/10.1109/GLC.2019.8864126 | ECO | 1.1 | C |
| Li, C., Zhang, X., Tangdiongga, E., Dai, X., Tsai, C. T., Wang, H. Y., ... Koonen, T. (2019). Cost-efficient half-duplex 10-Gbit/s all-optical indoor optical wireless communication enabled by a low-cost Fabry-Perot laser/photodetector. Optics Letters, 44(5), 1158-1161. https://doi.org/10.1364/OL.44.001158 | ECO | 1.1 | J |
| Ma, Q., Li, C., Zhang, Y., Dai, X., Cao, Z., Liu, Y., & Xiang, Y. (2019). Low cost λ-tunable transmitter for indoor infrared wireless communication system. Optics Communications, 448, 60-63. https://doi.org/10.1016/j.optcom.2019.05.004 | ECO | 1.1 | J |
| Morant, M., Trinidad, A. M., Tangdiongga, E., Koonen, T., & Llorente, R. (2019). Experimental demonstration of mm-Wave 5G NR photonic beamforming based on ORRs and multicore fiber. IEEE Transactions on Microwave Theory and Techniques, 67(7), 2928-2935. [8641363]. https://doi.org/10.1109/TMTT.2019.2894402 | ECO | 1.1 | J |
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