PROJECT FINAL REPORT (Public Part)

Grant Agreement number: 248609

Project acronym: SOFI

Project title: Silicon-Organic hybrid Fabrication platform for Integrated circuits

Funding Scheme: Collaborative project, small or medium-scale focused research project

Date of latest version of Annex I against which the assessment will be made: 2012-03-20 (Version 2.3, approved by EC on 2012-05-10)

Periodic report: 3rd

Period covered: from 2012-07-01 to 2013-06-31

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Silicon-Organic hybrid Fabrication platform for Integrated circuits

FINAL REPORT (Public Part)

Deliverable no.: D1.7
Due date: 2013-08-29 (60 days after end of review period)
Actual Submission date: 2012-07-15 (before review meeting)
2013-12-17 (update)

Authors: KIT, SELEX, IMEC, RB, AIT, GO, CUDOS
Work package(s): all
Distribution level: PU[1]
Nature: document, available online at the SOFI webpage

List of Partners concerned

Partner number	**Partner name**	**Partner short name**	**Country**	**Date enter project**	**Date exit project**
1 (coordinator)	Karlsruhe Institute of Technology (formerly University of Karlsruhe)	KIT	Germany	M1	M42
2	SELEX - Sistemi Integrati	SELEX	Italy	M1	M42
3	Interuniversity Microelectronics Centre - IMEC	IMEC	Belgium	M1	M42
4	Rainbow Photonics AG	RB	Switzerland	M1	M42
5	GigOptix-Helix AG	GO	Switzerland	M1	M42
6	Research and Education Laboratory in Information Technologies	AIT	Greece	M1	M42
7	The University of Sydney, Centre for Ultrahigh bandwidth Devices for Optical Systems	CUDOS	Australia	M1	M42

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[1] **PU** = Public
PP = Restricted to other programme participants (including the Commission Services)
RE = Restricted to a group specified by the consortium (including the Commission Services)
CO = Confidential, only for members of the consortium (including the Commission Services)

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Contents

1 Executive summary

The SOFI project responded to the disruptive photonics FP7-call 4, and reached its very ambitious objectives. New active optical waveguides and integrated optoelectronic circuits based on a novel silicon-organic hybrid (SOH) technology are introduced in the domain of Silicon Photonics. The technology is based on the low-cost CMOS process technology for fabrication of the optical waveguides - allowing for the convergence of electronics with optics. It is complemented by an organic layer that brings in new functionalities so far not available in silicon.

SOFI provides a proof-of-concept implementation of ultra-fast, ultra-low energy optical modulators such as needed in optical communications and microwave photonics. The demonstrated prototypes address the most important principal challenges of today, concerning:

- ✓ Data transmission capacity: SOH IQ modulators can operate at 28 GBd using 16QAM to transmit 112 Gbit/s on a single channel and single polarization [1].
- ✓ Bandwidth: SOH phase modulators can exceed 100 GHz [2].
- ✓ Energy consumption objectives have been reached [3] (further results in publication).
- ✓ Driving voltage: Ultra-low $V_\pi L$ products have been realized [3] enabling, e.g., efficient comb line generation [4].

However, the SOFI technology is even more fundamental. By varying the characteristics of the organic layer highly energy efficient switches employing liquid crystals have been demonstrated [5]. Using dye molecules as cladding, SOH lasers [6], [7] surpass any other laser on silicon by an order of magnitude in peak output power. The SOFI Consortium, which created this Silicon-Organic Hybrid Fabrication Platform, consists of:

KIT designed and in part built the device prototypes and performed the demonstrations mentioned above in its labs. In addition KIT coordinated the SOFI project and disseminated its results on numerous conferences and industry meetings.

AIT as a centre of excellence for research and education in the fields of ICT found the participation in SOFI as a great opportunity to spread generated knowledge through educational and industry oriented courses, to prepare specialized teaching material and to improve further its industrial collaborations. In SOFI, AIT was mainly involved to identify the linear and non-linear potential applications for the developed integrated photonic components, to investigate the system level specifications by simulation for each of the respective potential applications. Aiming for future low-cost, energy efficient and ultra-high bandwidth optical subsystems, AIT evaluated the efficiency of the proposed solutions in terms of cost and green aspects with respect to the existing technology solutions.

IMEC's commitment in SOFI is to extend its silicon photonics platform to silicon-organic hybrid devices. This includes the development of low-loss slot waveguides, specific dopant implantation steps, and the final opening of the cladding layers to infiltrate the electro-optic polymers. Slot waveguide losses fell short of the objectives at 10dB/cm, but good enough to demonstrate working devices. The back-end opening process was successfully demonstrated at sample level, and is currently under development at wafer-scale level. In the fabrication of the functional demonstration devices, IMEC has incurred significant delays, due to a combination of delayed designs, tool failures and maintenance.

Rainbow Photonics has developed thin-film organic crystalline deposition techniques on top of structured silicon chips. Melt growth has been found in particular promising for the aims of SOFI, due to the possibility of filling nanostructures like slot waveguides with less than 100-nm in size. First demonstration of high-speed modulation at 12.5 Gbit/s and $V_\pi L$ of 12 V mm has been possible in an SOH device utilizing a single crystalline organic film of BNA. The results of the SOFI project open up a new opportunity for organic single crystals to replace poled polymers in SOH applications where high long-term stability, resistance to high optical powers and temperatures, and parallelism is required.

CUDOS provided deposition of Chalcogenide glasses, as an inorganic alternative for benchmarking purposes.

SELEX ES used the SOFI project as an opportunity to develop critical optical components and to acquire expertise in the Silicon Photonics technology. The role of SELEX in the project was the RF design and to supply the packaging solutions.

GigOptix-Helix provided the core competences related to the modulator driver electronics and electro-optical polymer material. In particular GigOptix-Helix performed a study for an optimized driver for the SOFI modulator and proved with KIT the feasibility of driving a SOFI modulator with an integrated Silicon-Germanium (SiGe) driver. This result is of particular importance since the possibility to drive the SOFI modulator with SiGe drivers paves the way to extremely compact low power multi-channel TOSAs in which the SOFI modulators shall provide a distinct advantage with respect to competing technologies. Regarding the electro-optic polymer material, GigOptix supported the design activities and process developments for the SOFI modulator. GigOptix-Helix was also in charge of the supply of the actual electro-optical material produced at GigOptix which was used in SOFI modulators.

The SOFI approach proved to be disruptive and practical on a prototype scale. It combines the silicon CMOS technology and its standardized processes with the manifold possibilities offered by novel organic materials.

2 Summary description of project context and objectives

Silicon-Organic hybrid Fabrication platform for Integrated circuits

At A Glance

www.sofi-ict.eu

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Timeline
Start Date: 01/01/2010
End Date: 31/06/2013

Budget
Overall Cost: >3.5 M€
EC Funding: 2.5 M€

Delivered a proof-of-concept of

- The silicon-organic hybrid fabrication platform
- Implementation of high speed electro-optic modulators at 112 Gbit/s to show the platform's potential
- Ultra-low energy modulators at 12.5 Gbit/s
- Applications beyond data / telecom domain, demonstrating lasers and switches

Project Partners

- Karlsruhe Institute of Technology (KIT), DE
- Selex ES, IT
- IMEC, BE
- Rainbow Photonics AG, CH
- GigOptix-Helix AG, CH
- Research And Education Laboratory In Information Technologies (AIT), GR
- Australian National University, the University of Sydney (CUDOS), AU

Vision & Aim

In the SOFI project, new active optical waveguides and integrated optoelectronic circuits based on a novel silicon-organic hybrid technology are introduced. **The technology is based on the low-cost CMOS process technology for fabrication of the optical waveguides - allowing for the convergence of electronics with optics. It is complemented by an organic layer that brings in new functionalities** so far not available in silicon.

SOFI focuses on a proof-of-concept implementation of ultra-fast, ultra-low energy optical phase modulator waveguides such as needed in optical communications. These devices will ultimately be used to demonstrate an integrated circuit enabling the aggregation of low-bitrate electrical signals into a 400 Gbit/s OFDM data-stream **having low energy consumption.**

By varying the characteristics of the organic layer one may also envision new sensing applications for environment and medicine.

The suggested approach is practical and disruptive. It combines the silicon CMOS technology and its standardized processes with the manifold possibilities offered by novel organic materials. This way, for instance, the processing speed limitations inherent in silicon are overcome, and an order-of-magnitude improvement can be achieved. More importantly, the new technology provides the lowest power consumption. The potential for low power consumption is attributed to the tiny dimensions of the devices and to the fact, that optical switching is performed in the highly nonlinear cladding organic material rather than in silicon.

Main Objectives

1. Development of a silicon-organic hybrid (SOH) integrated optics platform
    - Overcome silicon related limitations such as the missing electro-optic effect
    - Deal with all technological aspects such as deposition of organics, poling, metallization & prototype packaging
2. Realization of EO phase modulator with 100 GHz electro-optic bandwidth at 1550 nm
    - This will ultimately increase optical processing speeds beyond today's limits of silicon
3. Demonstration of integrated optical circuit for higher order signal modulation formats at 100 Gbit/s
    - Mach Zehnder modulator configuration
    - 50 Gbit/s QPSK, 100 Gbit/s using advanced modulation formats in system application scenario
4. Look into silicon-organic hybrid technology for other purposes than data / telecom applications
5. Benchmarking with respect to other data / telecom technologies
    - Evaluate potential of organic vs. inorganic material
    - Comparison to state-of-the-art LiNbO3, GaAs modulators

Technical Approach and Achievements

SOFI provided a proof-of-concept implementation of ultra-fast, ultra-low energy optical modulators such as needed in optical communications and microwave photonics. Claddings made of polymers containing optically nonlinear chromophores have been used, as well as claddings of organic crystals. The demonstrated prototypes address the most important principal challenges of today, in terms of:

- ✓ Data transmission capacity: SOH IQ modulators can operate at 28 GBd using QPSK for 56 Gbit/s or 16QAM to transmit 112 Gbit/s on a single channel and single polarization.
- ✓ Bandwidth: SOH phase modulators can exceed 100 GHz.
- ✓ Energy consumption goals realized by achieving ultra-low drive voltages. This enables, e.g., efficient comb line generation.

In addition, transmission using orthogonal frequency division multiplexing (OFDM) has been investigated. However, the SOFI technology is even more fundamental. By varying the characteristics of the organic layer highly energy efficient switches employing liquid crystals have been demonstrated. Using dye molecules as cladding, SOH lasers surpass any other laser on silicon in peak output power.

For these accomplishments the interplay of SOFI partners is crucial and is described in the brief summary below.

Guiding SOFI to address actual challenges of commercial relevance, **AIT** identified a number of potential applications of SOFI devices which exploit electrical and linear / nonlinear optical properties of SOH technology. Using the VPI transmission maker software tool, AIT built a simulation platform to study the impact of characteristics and device parameters of SOFI modulators on the systems performance in network systems scenarios, e.g. 56 QPSK systems, 112 Gbit/s DP-QPSK systems and 100 Gbit/s optical OFDM. A block diagram of the 100 Gbit/s DP-QPSK transmitter and receiver is shown in Figure 2. After identifying the SOFI potential applications, the system specifications and component requirements for the silicon organic hybrid (SOH) devices were investigated. These activities took into account current standardization efforts, recent advances in 100 Gb/s and beyond high speed transmission systems as well as 10 Gb/s and beyond access networks which all rely on the generation of advanced modulation formats (Figure 1). These advances represent a promising context for the application of the SOFI SOH as a low-cost and high performance technology capable to provide modulator components, meeting the specifications of new generation high speed optical transmission interfaces.

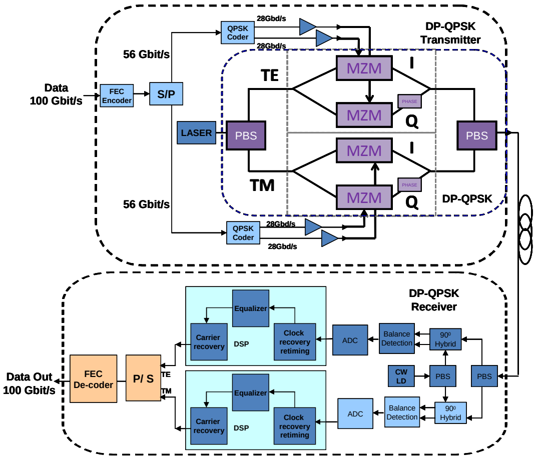


Figure 1. Block diagram of 100 Gbit/s DP-QPSK transmitter and receiver configurations.

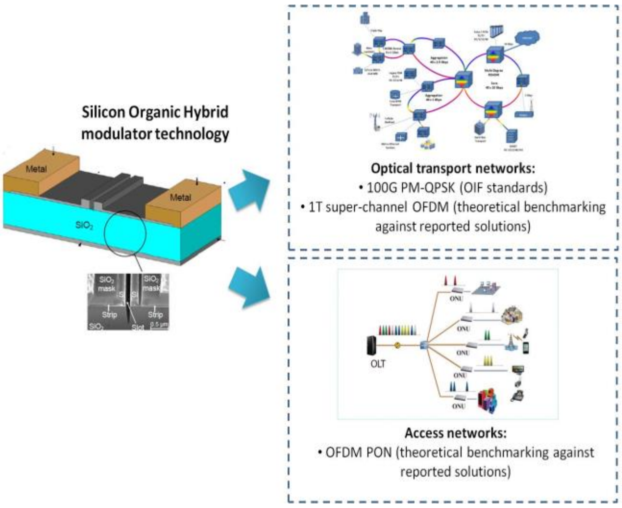


Figure 2. Specification definition structure of SOH modulator technology for long and short reach optical networks.

Finally, analytical results on the power consumption and cost related issues of the proposed SOFI's modulators were demonstrated, emphasizing on novel applications targeting 400 Gb/s. These studies included the investigation of the benefits when SOFI devices are applied in real communication systems taking into account the low power consumption of the developed materials. These studies also include a comparison of the SOFI devices with other commercially available and prototype solutions in terms of power consumption. Based on these studies it was extracted that a significant lower network energy requirement in the order of 22-25% can be achieved compared to standard commercially available solutions if SOFI's modulator technology is applied to a real communication system.

IMEC's role in SOFI is to extend its silicon photonics technology platform to accommodate hybridization, with a focus on silicon-organic hybrid devices. For this, the platform needed to be extended in a way that does not impact the other components in a detrimental way. This includes the development of generic platform modules (not specific to SOFI) and extensions modules (specific to SOFI, but compatible with the rest of the platform process. These latter modules are the patterning of low-loss slot waveguides, specific dopant implantation steps, and the final opening of the metallization layers to infiltrate the electro-optic polymers. Non-specific modules that were developed during the project are silicidation, tungsten contacting and copper/aluminium metallization.

Slot waveguide performance fell short of the objectives: Using the best lithographic patterning available in the 200 mm line, we could not produce slot waveguides with the targeted loss of 5 dB/cm, but still managed to be on par with the state-of-the-art at 10 dB/cm. The implantation conditions for slot modulators were explored and have yielded functional devices designed by KIT. The back-end opening process was successfully demonstrated at sample level, and is currently under development at wafer-scale level.

The figure below shows a cross- section of a device from the SOFI 2 run with a slot waveguide, electrical contacts and an etched back-end opening.

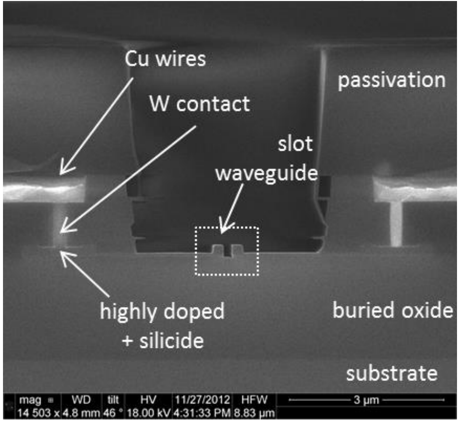


Figure 3. Cross-section of a device from the SOFI 2 run with a strip-loaded slot waveguide, electrical contacts and an etched back-end opening

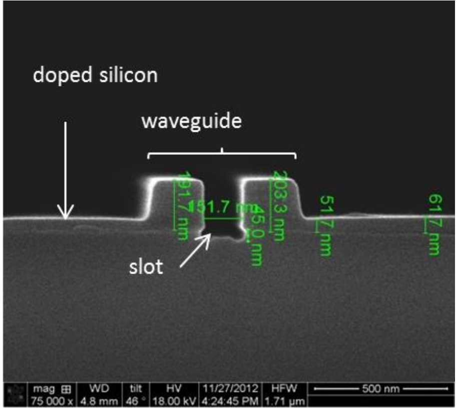


Figure 4. Cross-section of a strip-loaded slot waveguide, magnification of previous figure.

The most important task of IMEC was the fabrication of the functional devices for further experiments by the other partners. Here, IMEC has incurred significant delays, due to a combination of difficult process development in the low-loss slot waveguides, delayed design contributions, processing tool failures and maintenance.

Rainbow Photonics is the worldwide only commercial producer of high-optical-nonlinearity organic single crystals such as DAST, DSTMS and OH1, in a bulk form for applications such as frequency conversion, THz-wave generation and electro-optics. In the SOFI project, RB has developed several thin-film organic crystalline deposition techniques on top of structured silicon chips, which has a high potential to improve the efficiency compared to bulk applications by several orders of magnitude. In particular, melt growth has been found promising for the aims of SOFI, due to the possibility of filling nanostructures like slot waveguides with less than 100-nm in size. Figure 5 shows an example of a single crystalline BNA film covering a SOFI2 waveguide.

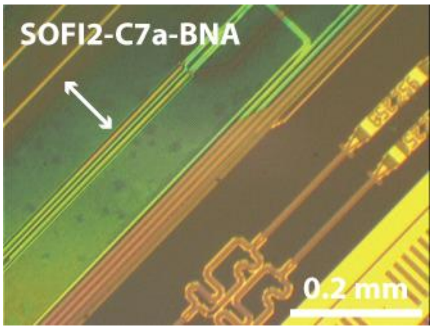
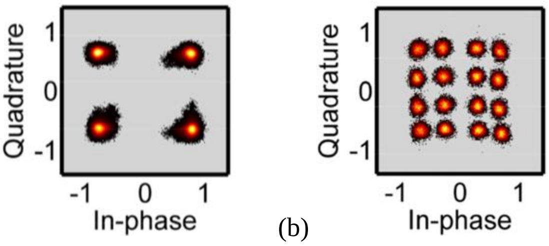


Figure 5**:** Example of a SOFI2 modulator covered with a single crystalline BNA film oriented with the polar axis (white arrow) normal to the waveguide direction, which is ideal for electro-optic modulation.

A first demonstration of high-speed amplitude modulation at 12.5 Gbit/s and $V_\pi L$ of 12 V mm has been possible in an SOH Mach-Zehnder device utilizing a single crystalline organic film of BNA. The results of the SOFI project open up a new opportunity for organic single crystals to replace poled polymers in SOH applications where high long-term stability, resistance to high optical powers and temperatures, and parallelism is required.

CUDOS has provided deposition of Chalcogenide glasses, as an inorganic alternative for benchmarking purposes. A complete filling of the slot waveguide has been achieved.

Design of the optical waveguides and high-speed RF-electrodes was done by **Karlsruhe Institute of Technology (KIT)**. After fabrication by IMEC and deposition of material by/from RB, GO and CUDOS prototypes have been characterized in KIT's laboratories. 16QAM has been demonstrated using an SOH IQ modulator at 28 GBd delivering 112 Gbit/s, as shown in the next figure. Also energy consumption and bandwidth records have been set in the domain of Silicon Photonics.



(a) (b)

Figure 6. Constellation diagrams of SOH IQ modulator operated at 28 GBd providing a data rate of (a) 56 Gbit/s and (b) 112 Gbit/s below standard forward error correction limits using driving signal pre-emphasis. [Figure source: Optics Express, Vol. 21, Issue 11, pp. 13219-13227 (2013)]

SELEX ES is involved in several research activities in the field of the microwave photonics for civil and military applications. It focuses on the improvement of its line of products performances at system level (RADAR optical Link) and at component level (optical modulator, switch, filters).

The SOFI project represented an opportunity to develop optical components which are fundamental blocks that promise to move a step forward from the current technologies in terms of costs, efficiency and size.

SELEX realized its main objective, i.e., to acquire more expertise in the Silicon Photonics technology, exploring also electro optical properties of the organic materials, to test new microwave concepts for device packaging and RF connections.

The tasks performed by Selex rely on the RF design, on the packaging solutions and on the device characterization. In particular Selex contributed to the design of the RF electrodes of the modulator, to the definition of the flip-chip method for the packaging, to the design and realization of the casing, and design and realization of the tool used for fiber pigtails.

Finally a packaged prototype has been realized.

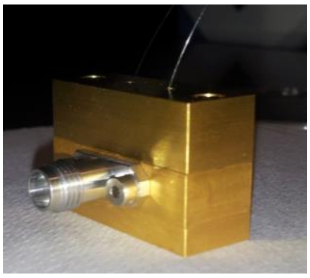


Figure 7. SOFI2 Final packaged prototype.

GigOptix is a fabless semiconductor company designing solutions for the cloud and high speed networks and applications. Its customer base includes global Tier 1 & 2 equipment OEMs and ODMs. GigOptix focused mission is to be an industrial leader in analog devices that enable high-speed information streaming links over the networks, end to end. The most relevant aspects in SOFI as far as GigOptix is concerned are:

- The development of a technology yielding very compact and complex modulators capable of high speed operations and that can be operated in linear mode.
- The monolithic CMOS integration of the transmitter electronics with the modulator.

Expected impact

Technical results come to the benefit of the participating industrial partners and people reading our publications. However, the impact of the project must be seen in the wider context of several European and international incentives in the domain of Silicon Photonics.

Being part of the European Silicon Photonics Cluster (see www.siliconphotonics.eu), **SOFI demonstrated that the silicon-organic hybrid platform contributes a viable technology to face today’s global questions on capacity of communication channels** (be it long distance connections for the internet or some optical port to connect PCs, servers) and their related **energy consumption**.

Given the fact that huge microelectronics companies are driving research in this field, **SOFI creates know-how specifically in Europe** in a field where nobody yet can claim leadership.

Considering the almost infinite range of applications which come into view at the moment of convergence between electronics and photonics, **SOFI identified the particular set of applications which can be served best by using the silicon organic hybrid approach**. In this sense, SOFI is a piece in an ensemble of European projects driving innovation in Silicon Photonics in the EU and thereby creating potential for employment and wealth in general.

3 Main S&T results/foregrounds

3.1 Identified SOH modulator application scenarios

From the very first steps of the project, **AIT** had identified a number of different applications based on projected capabilities of the SOH technology.
Taking into account the requirements for the realization of such applications, AIT provided the initial definitions of SOFI modulator and module specifications for device and system applications. Considering this initial input and with respect to high-speed optical transmission systems, the target applications identified included 100 Gb/s and beyond coherent systems based on PM-QPSK and super channel Co-OFDM that were applied and investigated for new generation high capacity optical transport networks.

The target specifications and requirements for the SOFI SOH modulators took into account the latest standardization efforts in 100 Gb/s transmission systems and feedback from the SOFI devices characterization. More specifically a specification analysis for long reach optical networks for **100 Gbit/s and 1 Tbit/s systems** was performed**.** The analysis was based on transmission modeling studies that involved benchmarking of the SOH modulator technology against commercially available electro-optic modulators (e.g. LiNbO3) and currently researched low-cost silicon modulator approaches.

In addition, the specification study was expanded to cover optical access networks taking into account recent advances in **short-reach** (access) optical networks that foresee the penetration of OFDM in passive optical networks (PONs) in order to satisfy the need for speed and bandwidth flexibility in Next Generation PONs (NGPONs). Figure 8 and Figure 9 show the simulation setups used to evaluate the performance of SOH modulators against other solutions for long haul and PON networks respectively.

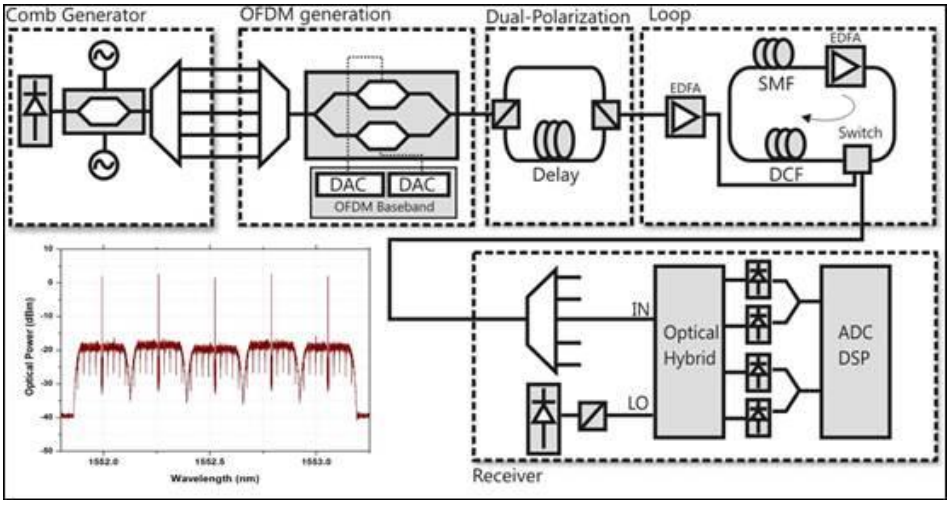


Figure 8. Multi-carrier Co-OFDM simulation testbed, inset: OFDM signal spectrum, inset: optical spectra of the five 30 GHz spaced Co-OFDM channels.

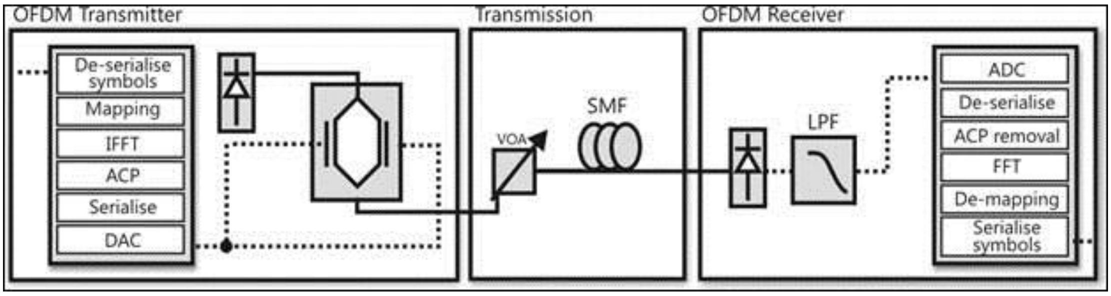


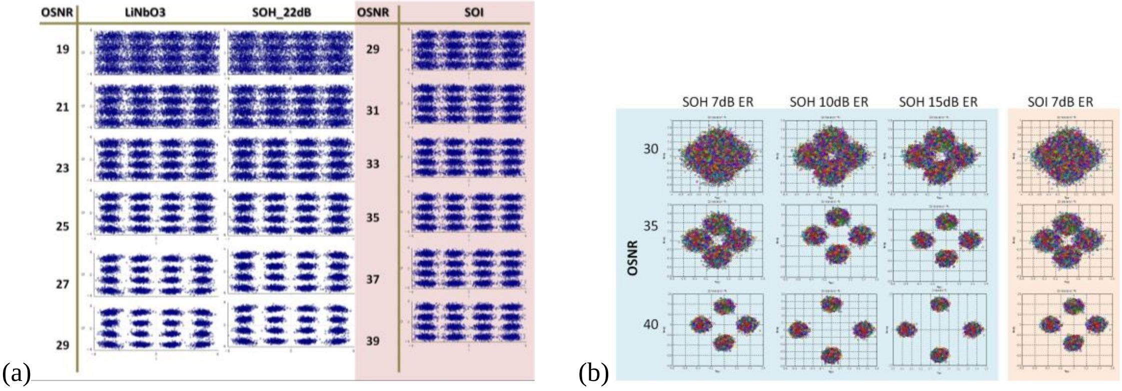
Figure 9. Transmission link model for OFDM-PON transmission study.

The simulation results showed that in order to be considered a competitive solution for future optical transport systems SOH modulators must first be compliant with the 100G baseline specifications set by OIF standards. The specification analysis for 100G systems revealed that SOH modulators are capable to meet the device bandwidth specifications

(23 GHz) and the operating voltage specifications (5 V) given the SOH technology advances with respect to poling efficiency, RF electrode/waveguide distance and slot size. In addition, due to their small size, SOH modulators are able to fit into the specified 100G PM-QPSK modulator mechanical packages and represent an ideal solution for size reduction of new generation optical transport systems due to the dense array integration potential.

With respect to future 1 Tb/s OFDM-based optical transport systems, SOH modulators have the potential to over-pass mainstream LiNbO3 components since they can provide the necessary 3-dB bandwidth in a much smaller size, but this has to be accommodated with a comparable ER of >20 dB. In addition, the specification studies showed that given the present development status, new low-cost silicon modulator approaches cannot compete with SOH components, unless great effort is spent to circumvent their inherent slower dynamics which limits the operating speed as well as the <10 dB extinction ratios, which restrict their employment in short reach applications (see the following specification analysis for short reach).

Moreover in the case of NG-PON OFDM-based networks it was clear that the SOH devices can provide an ideal solution for developing low-cost optical transceivers. In terms of device specifications, the device bandwidth is sufficient to cover the speed targets of NG-PONs. Considerable performance improvement compared to silicon modulators is feasible given that the SOH technology can provide devices with an ER >10 dB. Figure 10 a) and b) show constellation diagrams indicating the performance of SOFI devices against other available solutions for long haul and PON networks respectively.



(a) (b)

Figure 10. (a) Typical recovered subcarrier constellations for 500 km. (b) Typical recovered subcarrier constellations for the SOH and silicon modulators.

3.2 SOH modulator power consumption in communication system scenario

After the performance evaluation of the SOFI devices in a system simulation environment, analytical results on the power consumption and cost related issues of the proposed SOFI's modulators were demonstrated, emphasizing on novel applications targeting 400Gb/s. These studies included the investigation of the benefits when SOFI devices are applied in real communication systems taking into account the low power consumption of the developed materials.

Table 1 shows the power consumption calculations extracted when using devices of different technologies in OFDM transmitters/transponders for 16-QAM and QPSK modulation formats. These studies also included a comparison of the SOFI devices with other commercial available and prototype solutions in terms of power consumption. Based on the above studies relevant network planning studies were performed showing that a significant **lower network energy requirement in the order of 22-25% can be achieved** compared to standard transceiver solutions if SOFI's modulator technology is applied to a real network. Moreover, a relevant study based on cost of proposed transponders targeting 100GHz bandwidth compared to currently available 50 GHz bandwidth transponders was performed highlighting the benefits of the SOFI's technology from a wider point of view in terms of cost reduction.

Table 1. Power consumption calculations extracted when using devices of different technologies in OFDM transmitters/transponders for 16-QAM and QPSK modulation formats

Output Voltage	**OFDM 400Gb/s Transmitter Power consumption**	**OFDM 16-QAM 400Gb/s transponder Power consumption**	**OFDM QPSK 200Gb/s Transmitter Power consumption**	**OFDM QPSK 200Gb/s transponder Power consumption**
SOFI targeted 1Vp-p	23.28W	92.22W	19.04W	73.28W
SOFI expected 2.5Vp-p	28.60W	97.54W	21.70W	75.94W
SOH achieved 4Vp-p	42.96W	111.90W	28.88W	83.12W
SOFI achieved 6Vp-p	58.96W	127.90W	36.88W	91.12W
SOFI achieved 5Vp-p	50.12W	118.23W	32.73W	93.47W
Typical LiNbO3 7Vp-p	67.44W	136.38W	41.12W	95.36W
InP modulators 4Vp-p	42.96W	111.90W	28.88W	83.12W
Polymer based 2.5-3Vp-p	28.60W	97.54W	21.70W	75.94W
LiNbO$_3$ prototypes 1Vp-p	23.28W	92.22W	19.04W	73.28W

3.3 Identified additional disruptive SOH application scenarios

The core of the SOFI project's idea was to unite the advantages of the silicon platform with the virtually unlimited possibilities of organic cover materials for a variety of purposes. In this framework the range of SOH applications proven to work extended by introducing:

1. The first SOH laser.
2. Ultra-low power phase shifters useful for adjusting inevitable phase deviations in the fabrication of IQ modulators and optical FFT circuits for OFDM.

The first SOH laser at a telecommunication wavelength of 1310 nm has been demonstrated in silicon-organic slot waveguides with dye-doped PMMA cladding and presented the first demonstration of an active, light emitting silicon-organic hybrid waveguide. It is not suited for telecommunication, due to its low duty cycle and limited lifetime, but its emission wavelength makes it compatible to existing, highly optimized technological solutions for processing and sensitive high-speed detection in other application areas, such as sensing and spectroscopy. More recent devices as shown in Figure 11 surpass any other IR silicon-based laser in terms of peak power. This is enough power to consider using the laser for applications on-chip based on the nonlinear effect. This is a proof-of-principle and relies on an external pump laser (13.7 Hz pulsed beam at 1064 nm, 0.8 mJ and 1 ns per pulse) hitting a slot waveguide from the top. The cover material was simply spin-coated and baked at low temperature.

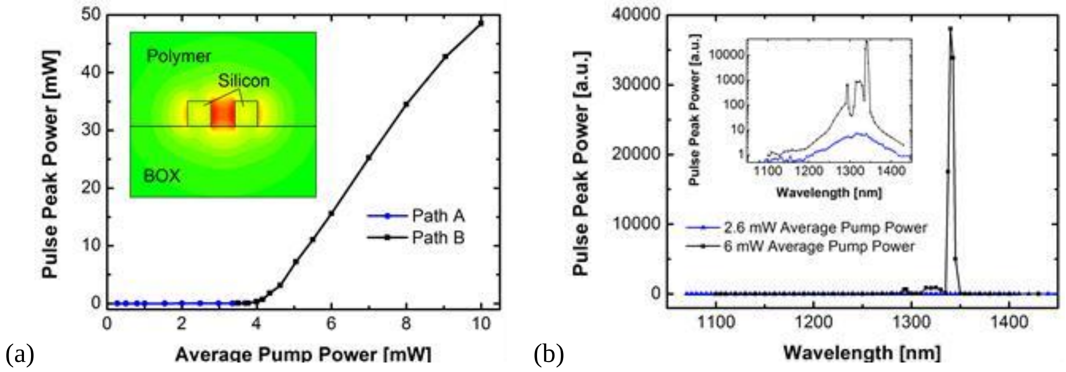


Figure 11. SOH Laser emission. (a) Output pulse peak power in fiber vs. averaged pump. The inset shows the slot waveguide with simulated mode field. (b) Emission spectrum at resolution bandwidth of 5 nm. Image source [6].

Liquid Crystal Phase Shifters have been built with $V_{pi}L$ = 0.085 Vmm and nW-power consumption. The device exploits slot-waveguides filled with liquid crystals. A drive voltage of 5 V leads to a 35 π phase shift as shown in Figure 12.

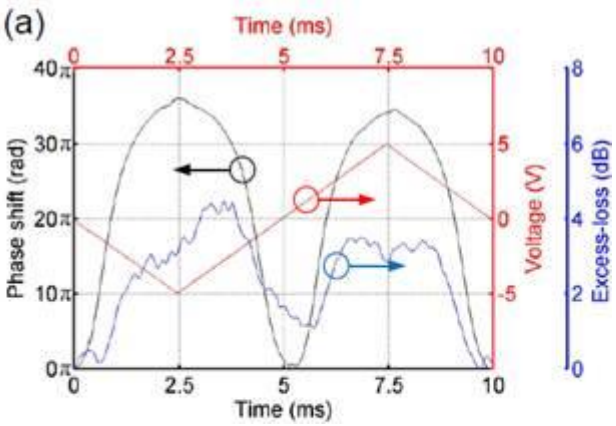
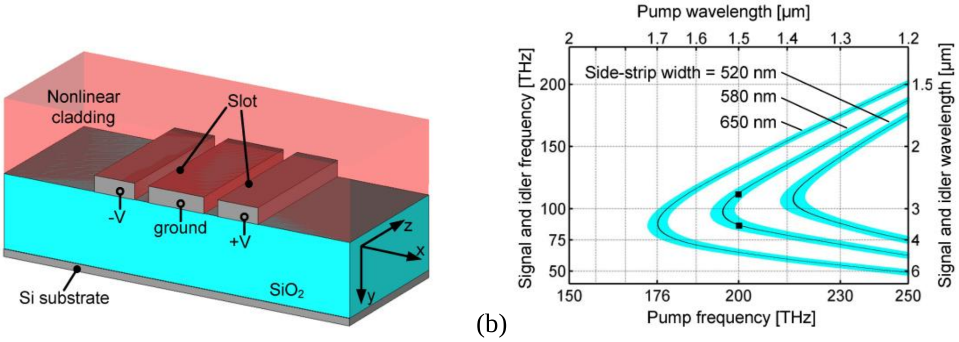


Figure 12. SOH Liquid crystal phase shifter on SOI. Measured phase shift of strip loaded slot waveguide filled with liquid crystals and driven with a 100 Hz triangular signal of 5 V. Image source [5].

Parametric amplification using organic $\chi^{(2)}$-nonlinear claddings should be particularly efficient, because of the strong confinement of light known in silicon photonics. **KIT** proposed a waveguide structure to overcome phase-matching limitations by involving high order modes to achieve mode phase-matching [8]. The proposed waveguide is shown in the next figure.



(a) (b)

Figure 13. Silicon organic-hybrid (SOH) double slot waveguide for second-order nonlinear applications. (a) The waveguide consists of three silicon strips on a glass substrate, it is multimode and dimensioned such that modal phase-matching is achieved. The waveguide is covered by a nonlinear cladding, which is poled during fabrication by applying the voltages –V and + V to the outermost strips while the central strip is grounded. As a result the nonlinear second-order susceptibility is high only inside the slots. (b) Signal and idler frequencies vs. pump frequency for three different geometries. The black curves specify for a given pump frequency the signal and idler frequencies which satisfy the energy conservation and the phase-matching condition. The cyan-colored regions indicate the frequency space where the coherent buildup length is equal to 1 cm or longer. The three different curves represent waveguides where the side-strip width is set to 520 nm, 580 nm and 650 nm. The central-strip width is 800 nm and the slot width is 200 nm in all the three cases. For a side-strip width of e.g. 580 nm and a pump wavelength of 1.5 µm (200 THz), signal and idler wavelengths of 2.6 µm and 3.5 µm would result (square symbols). Image source: [8].

A patent application has been filed by KIT. *‘Wellenleiter-Bauteil fuer nichtlinear-optische Prozesse zweiter Ordnung,’* L. Alloatti, J. Leuthold, W. Freude, C. Koos, D. Korn, and C. Weimann, Germany 102012016328.2 (2012).

Microwave Photonics. Finally **AIT collaborated with SELEX** to further investigate the potential applicability of SOFI devices on both military and civil fields. In particular, the activity was mainly focused on the improvement of the advanced generation of Multifunction Phased Array Radars (M-PAR), where high performance optical components are needed. Specifically, the integration of the SOFI modulators in such RADAR systems is used to perform Optical Beam Forming Networks as well as WDM based simultaneous functions and scalability. Figure 14 shows the architecture of an **optical beam forming network (OBFN)** architecture **based on wavelength division multiplexing (WDM) designed by SELEX and AIT where a large number of SOFI modulators** can be integrated within the same substrate exploiting several optical functions, such as the grating for wavelength routing.

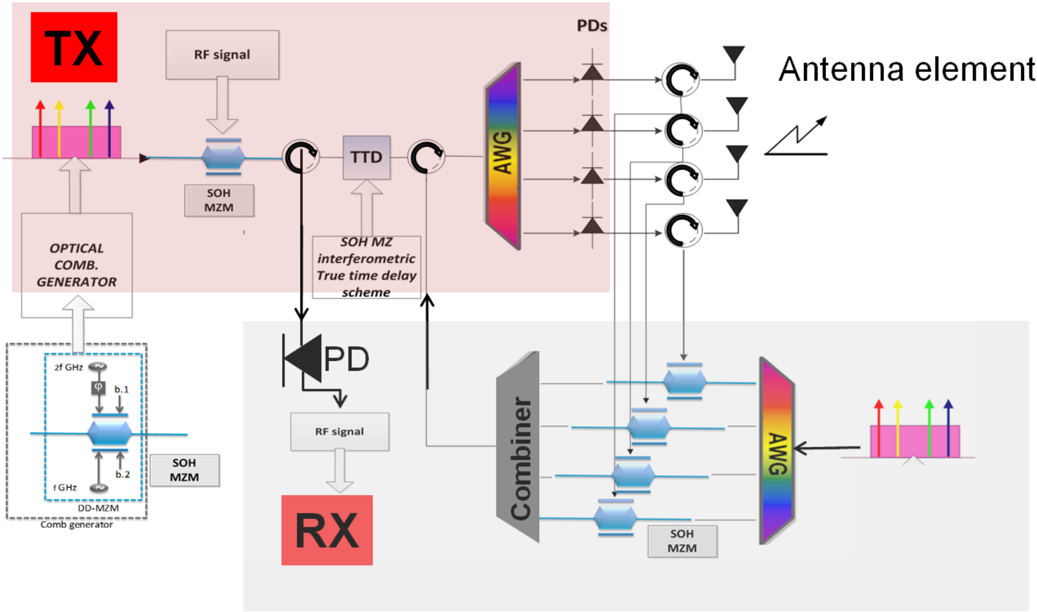


Figure 14. Microwave photonics for radar application. Optical beam forming network (OBFN) architecture based on wavelength division multiplexing (WDM).

3.4 SOH fabrication based on CMOS technology

IMEC's work focused on the extension of its technology platform to enable silicon-organic hybrids, and in particular the highly efficient, high-speed SOH modulators. At the start of the SOFI project, IMEC's silicon photonics technology platform consisted of world-class passive silicon photonics devices on 200mm SOI wafers. The platform development roadmap planned for an extension to incorporate plasma-dispersion modulators and germanium photodetectors, finished with a CMOS-compatible back-end process.

In the SOFI project, IMEC would develop additional modules to this platform. Together with the modules already in the roadmap, IMEC has developed during the SOFI project the following process capabilities:

1. **Slot waveguide patterning**: Efficient SOH modulators require low-loss slot waveguides. There are two main challenges in making good slot waveguides. First of all, the slot should be sufficiently narrow, i.e. ~100nm or less. This is a very aggressive feature for the optical lithography used in IMEC's 200mm line. In the SOFI project, IMEC experimented with several techniques to achieve such narrow slot waveguides: pattern transfer and phase-shift masks did not work. In the end, the introduction of a hard mask solved the problem. This process was carried and over from a parallel development to improve the future integration of active devices and tuned to yield 100nm slot waveguides. The results of the different processes are shown in the pictures below.

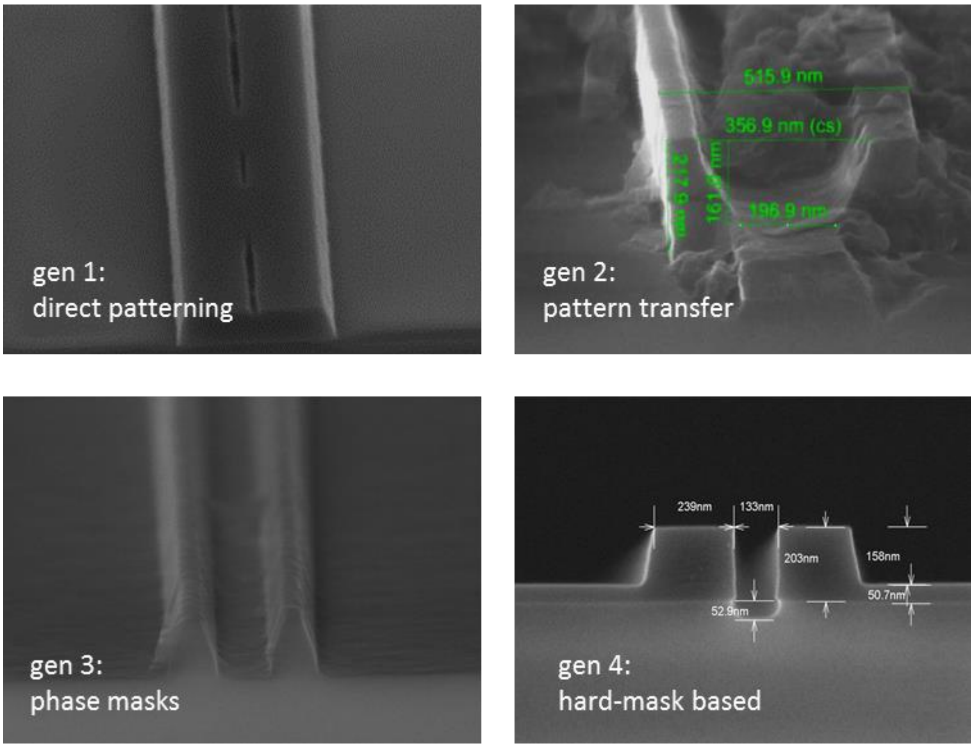


Figure 15. Evolution of slot waveguide patterning.

Secondly, the slot should be sufficiently smooth, to limit the scattering losses. This has proved to be very challenging, and the experimental results of the SOFI 2 device run show slot waveguide losses of the order of 10dB/cm, which is similar to demonstrations by other groups. After many unsuccessful attempts to improve the slot waveguide performance, we have come to the conclusions that better quality slot sidewalls are close to impossible to achieve with the available technology of the 200mm pilot line in IMEC.

However, significant improvement is possible with more advanced process technology. Running an experimental passive waveguide process in IMEC’s 300mm line in 2012-2013, we were able to demonstrate 100nm slot waveguides with a propagation loss below 4dB/cm. This could be achieved by making use of high-resolution immersion lithography at 193nm. Even though these are preliminary results from an experiment that was executed outside the scope of SOFI, the experiment shows potential improvement for later generations of SOH modulators or other slot-waveguide based devices.

2. **Dopant implantation**: Doped silicon waveguides are the key element in today’s silicon-based plasma-dispersion modulators. For SOH modulators, the requirement for doping is not used to manipulate carrier densities directly, but to provide a low-resistivity path to charge/discharge the capacitor over the slot, and thus applying an electric field over the EO-polymer inside the slot.

   Plasma-dispersion modulators with travelling wave electrodes have been fabricated, with operation up to 40 Gbit/s (characterization was performed with the help of KIT), and the learning from these devices was applied to the SOFI designs to improve doping conditions and electrode design.

   For the SOFI3 devices we applied double implantation to obtain an optimized doping profile in both the partially etched side cladding as in the waveguide. Results from these devices are still pending at the time of writing.

3. **Contacting and metallization**: The contacting and metallization modules are developed as a generic addition to the platform, and the processes were conceived in such a way that they are compatible with SOH devices. The objective was to adhere as much as possible to a standard CMOS back-end flow. For this, a Nickel-silicide was first formed on a highly doped silicon area. This NiSi alloy then provides a low-resistance ohmic contact between the Tungsten contact pillars and the silicon. The NiSi also acts as a selective stopping layer for the contact etch. The contacts are processed in a standard damascene process: the holes are etched in the planarized oxide cladding, filled with tungsten and the remaining tungsten layer is again polished away.

   A similar process is used for the copper metallization. One single metal routing layer was used. Finally, the wafer is finished with a SiON passivation layer and electrical contacts in AlCu are processed.

   The CMOS-compatible back-end metallization was applied in the second SOFI device run. For the first device run, the necessary back-end processes were not sufficiently well developed (and also, the mask was not yet designed with this process in mind). Therefore, Ti-Au electrodes were processed in the clean room in Ghent, on a sample basis.

Both the Cu/AlCu back-end, as well as the Ti-Au electrodes performed well and offered sufficiently high bandwidth for modulator operation well beyond 40 Gbps.

4. **Back-end opening**: Because the electro-optic polymers cannot be inserted during the processing of the slot, the waveguides need to be exposed again after the wafer has gone through the entire back-end metallization and passivation. This is not a trivial step, because there is no selective stop layer at the waveguide level to ensure the exact amount of cladding oxide is removed.
   For the SOFI1 devices, a non-CMOS backend was processed, and the slots were protected with a polymer to ensure they could easily be opened after the electrode processing.
   For the SOFI2 devices, the BEOL opening process was conducted in two stages: First, a dry etch was applied at wafer scale, and the remaining thickness was mapped over the entire wafer. Then the wafer was diced. Based on the thickness map, the individual samples were etched in the **Ghent or KIT** clean room with a timed HF etch. Loss measurements on modulator devices show that there is no significant impact on the waveguide quality because of this process, if timed correctly and an under-etch is avoided.
   For the SOFI3 devices, this process is adapted for wafer scale processing in imec. At the time of writing, the development is ongoing, and a dedicated wafer batch has been assigned for this development. A critical challenge in this development is avoiding the undercut in the slot.

The result of these different process modules is shown in the SEM pictures below: the slot waveguide in the center, sitting in an etched trench in the backend, where the copper and tungsten metallization is visible.

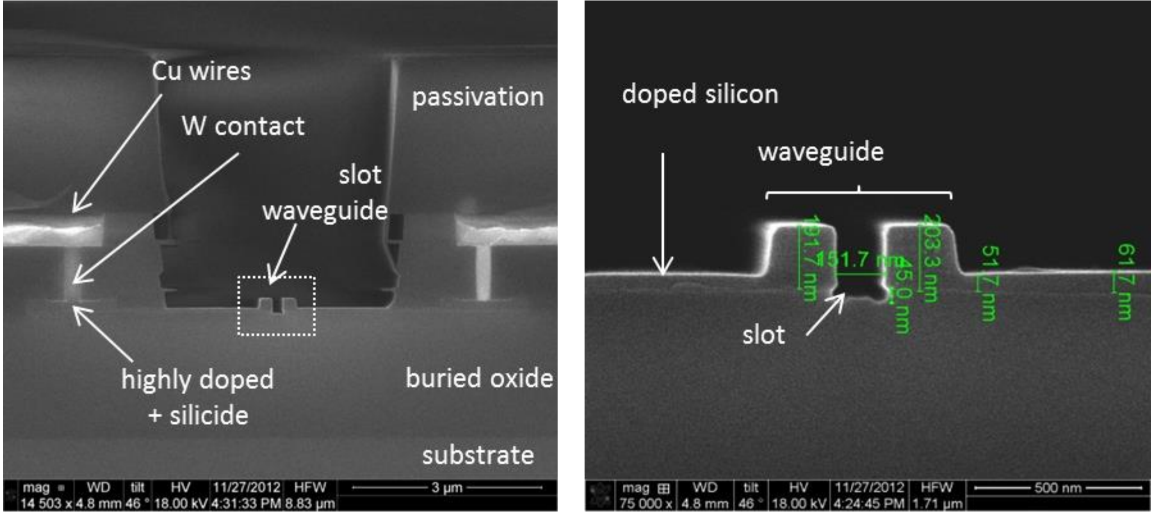


Figure 16. Strip-loaded slot waveguide exposed by back-end opening.

During the project, IMEC manufactured 3 batches of SOH devices, with increasing levels of complexity, both in design (mainly by KIT) and in process flow. While the manufacturing runs have suffered from serious delays, the resulting devices performed well on most accounts.

3.5 SOH functionalization

To equip passive silicon structures produced according to the methods present above, an organic cladding has to be added to “functionalize” (= add its new function) the waveguides and provide them with unique and superior properties not available from the pure SOI platform.

Rainbow Photonics selected and synthesized the best EO organic crystals known up to date. With these materials, two different deposition approaches have been investigated: solution growth and melt growth. We have shown that melt growth is much more compatible with silicon nanostructures requiring filling of silicon slot waveguides, therefore melt growth has been optimized for different materials and substrates considering seeding conditions, growth temperatures, temperature gradients and cooling rates to control the growth rates on differently structures SOI substrates.

The details of the deposition parameters depend on the particular material and may also vary depending on the chip type, i.e. wetting properties of the chip, which depend on the fabrication procedures prior to organic material deposition, in our case the fabrication procedures of the passive SOI structures by IMEC. Besides wetting properties, the deposition of organic crystals is obviously also affected by the geometry of the structures, for example by the depth and by the orientation of the trenches. However, the general growth procedure developed does not change considerably and is described below for the particular case of BNA material. With other materials, the main difference is the growth temperature (e.g., for OH1 it is above 200 ºC), seeding conditions (for OH1 only one heating cycle is used instead or two as best for BNA) and growth direction: with BNA it is optimal to grow the crystal along the waveguide direction, while for OH1 perpendicular to it.

The alignment of the optical axis of the organic crystal of BNA created on-chip can be verified with a reflection microscope by placing and rotating the sample between crossed polarizers relying on the birefringence of BNA, see . The achieved crystalline orientation is only approximately close to the optimal direction, which is because the growth direction was not restricted enough in the ac-plane, respectively xz-plane. (a) illustrates a deviation from the optimum by 15º. (b) shows the chip used for the data generation experiment by KIT. Its polar axis is 34° off the ideal direction. Additional growth-guiding trenches in unused regions of the chip or the cover glass could optimize this step, since for well-defined micro-size channels the growth direction is always perfectly aligned [9].

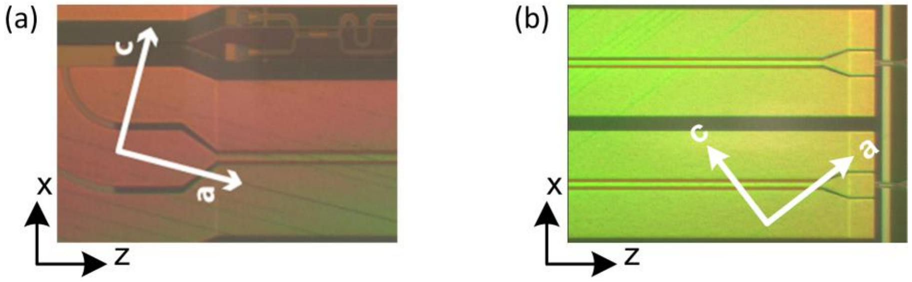


Figure 17. Microscope images of details on SOI chips (SOFI2-CMOS metal stack) covered with BNA single crystal between crossed polarizers utilizing the birefringence of the cladding BNA material. In case (a), the crystal is oriented about 15º from the optimal direction with the polar axis c normal to the WGs, while in case (b) this angle is about 34º. In both cases one single crystalline domain across multiple MZMs has been achieved.

In summary, we have been developed new melt deposition techniques for organic crystals to enable EO functionality of silicon waveguides. This we demonstrated using high-speed amplitude modulation at 12.5 Gbit/s in an SOH Mach-Zehnder device utilizing a single crystalline organic film.

GigOptix-Helix (GO) Related to the objective of identifying electro-optic polymers for operations at 85°C and high electro-optic coefficient (>100 pm/V at 1.55 µm light wavelength) suitable for use within SOFI, GO monitored the evolution of the GigOptix-Bothell electro-optic material. GO coordinated the intense exchange of sample material and work instructions between GigOptix Bothell (supplier to the consortium) and KIT.

Bonding the modulators by flip chip requires a temperature around 100°C. The M1 polymer from GO has a glass transition temperature T_g of 138°C. It is expected that the polymer properties degrade during flip chip bonding. GO has developed a new polymer M3, which has a higher T_g of 167°C, but also a higher optical loss (1.3 dB/cm instead of 1 dB/cm). GO provided the new polymer to KIT and KIT successfully poled the material.

3.6 Packaging of SOH devices

The SOFI project relies on vertically coupled SOI optical devices. Facing this issue, **SELEX** found a procedure enabling a stable chip to fiber alignment and fastening. The solution was to extend the contacting area of the fiber by the use of zirconium capillaries. Gluing the contact interfaces between the fiber and the SOI substrate results in a stable assembly.

A specific tool for fiber alignment and pigtailing has been designed and realized (see Figure 18). It consists of suitable fiber holders, stages for movement, support capillaries and polarization maintaining fibers. The fiber capillary is polished at an angle of 10° for an optimized optical coupling with the grating.

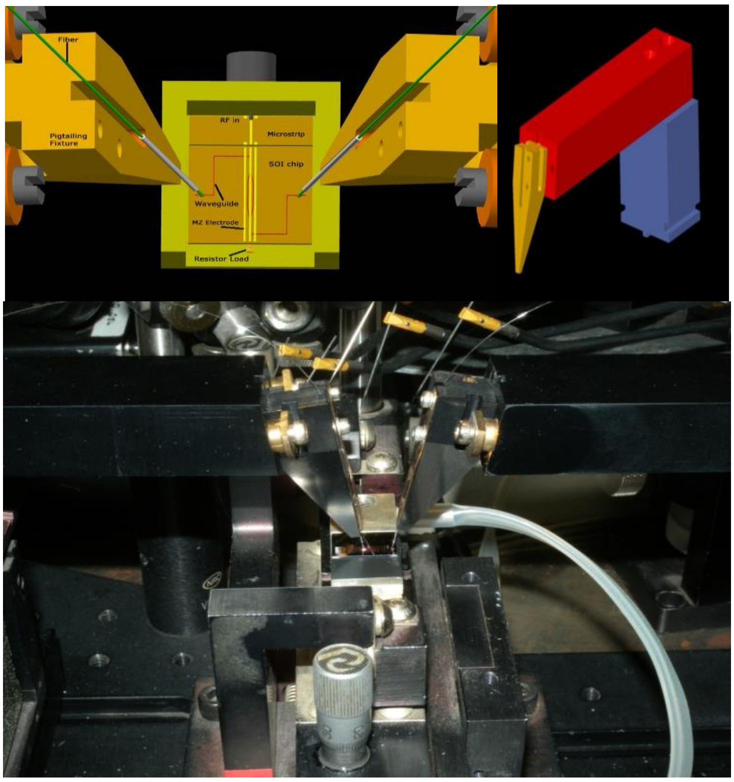


Figure 18. Tools for fiber alignment and pigtailing.

The first results of the fiber pigtailing were obtained with the chips coming from the SOFI1 run. Optical losses between 6.8 dB and 10 dB have been reported in 3mm long straight waveguides sampled from the wafer D07, D11 and D12 (see Figure 19). This includes two grating couplers which have 3 dB loss each, in the very best case.
One structure from the wafer D12, consisting on a longer curved waveguide (5.5mm) has been also pigtailed and electrically connected on a test carrier sample. The losses experienced are 14 dB.

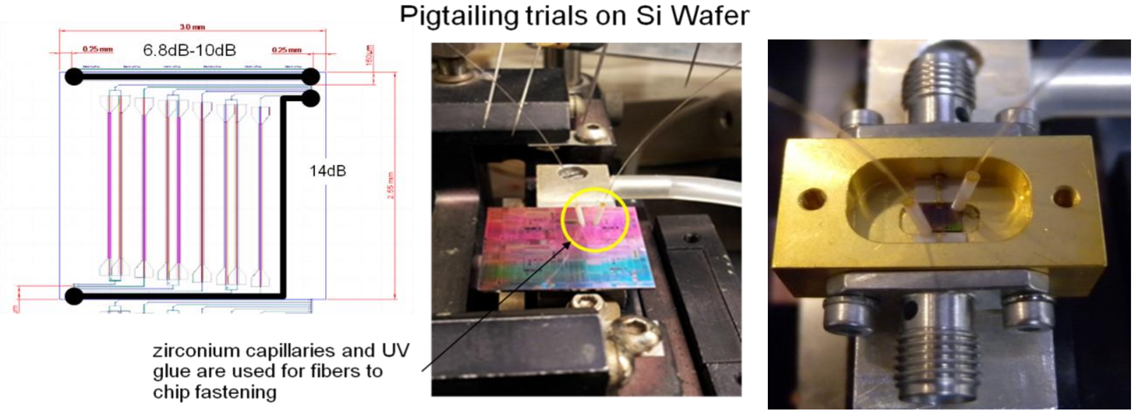


Figure 19. Polarization maintaining fiber glued on SOFI1 chip. Losses range from 6.8 dB to 10 dB for 3 mm straight waveguides, including 2 grating couplers. A longer curved waveguides (5.5 mm) has been also packaged in a chip carrier and electrically wired (optical losses 14 dB).

Several approaches have been investigated in order to connect the SOI input electrode to a standard input connector. The proposed final method consists of the flip-chip approach (see Figure 20). It has been chosen to reduce the wiring length as well as the RF losses and the related inductance.
The flip-chip approach is also more suitable for the industrialization of the connection procedure. For this aim, a suitable package has been realized. Considered the novelty of this approach, as well as the need to finalize a prototype, the package has been designed as flexible as possible, in order to allow for both flip-chip and standard wiring.

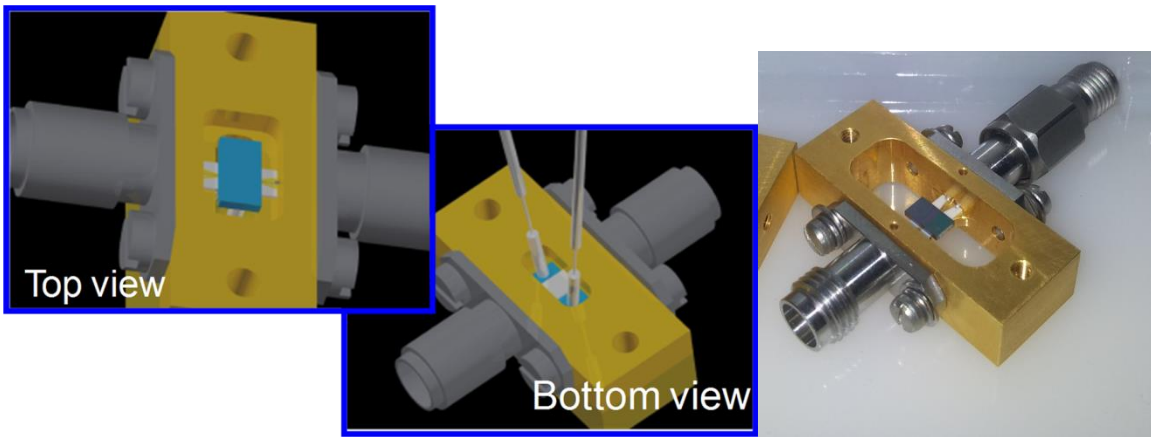


Figure 20: Flip-chip package, design (Si-chip in blue, alumina chip in white) and realization.

The main packaging difficulties stem from the integration of the SOI chip with the organic polymers that is used for the electro optic features.

In fact, on one side the flip-chip method is hard to realize (the polymer on the top of the chip avoids both electrical contacting between the SOI electrodes and the bumps, which serve as a fastening between SOI chip and the alumina substrate). On the other side, if standard wiring is exploited, the UV light used for fiber gluing damages the polymer (in the case of flip chip the alumina shadows the polymer).

3.7 SOH modulator characterization and benchmarking

SOH modulators have been characterized in the labs of **KIT**. Several subcomponents have been developed for this purpose.

A **strip-to-slot waveguide converter** was simulated, realized and characterized, see Figure 21. The work was published as [10].

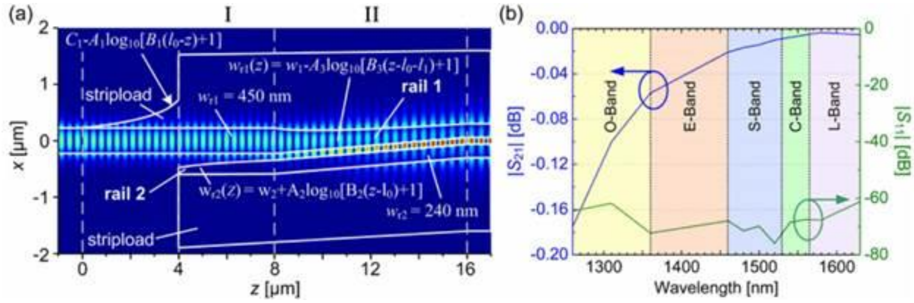


Figure 21. Simulation of a strip-to-slot waveguide converter. (a) Topview with electric field distribution in the logarithmically tapered strip-to-striploaded slot mode converter. (b) Transmission and reflection factors. Image source: [10].

SOH MZMs and SOH IQ modulators have been built following the concept shown in the next figure. Two nested MZMs constitute one IQ modulator. The phase modulator sections in each MZM are the strip-loaded socket waveguides. The slots are filled with the nonlinear material.

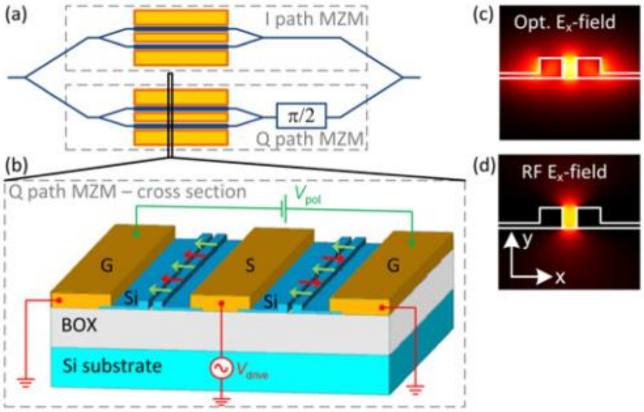


Figure 22. IQ modulator based on the SOH concept. (a) Topview of the IQ modulator with nested Mach-Zehnder modulators (MZM), displaying optical waveguides (WG) in blue and electrical lines in orange. (b) Cross section of an SOH MZM, showing two silicon striploaded slot WGs, which act as phase shifters. They are filled and covered with a nonlinear cladding (not shown for clarity). The coplanar RF transmission line (GSG, ground-signal-ground) is impedance matched to the driving signal generator. The RF voltage at the S-electrode creates oppositely directed electric slot fields (red arrows). During the fabrication process, the χ(2)-nonlinearity is created by applying a poling voltage between both RF ground (G) electrodes at an elevated temperature. This aligns (poles) the active cladding molecules in a direction indicated by green arrows. In combination with the poled cladding, the modulating RF voltage leads to opposite phase shifts in both interferometer arms. (c) Color-coded dominant x-component |Ex| of the optical electrical field in the slot WG cross section. (d) Modulating electrical RF field. Both fields are strongly confined to the slot, resulting in high modulation efficiency. Figure source: [1].

To make **SOH modulators**, this concept has been implemented by making use of a CMOS like metal stack as shown in the next figure. The results stem from a 2nd generation SOFI device.

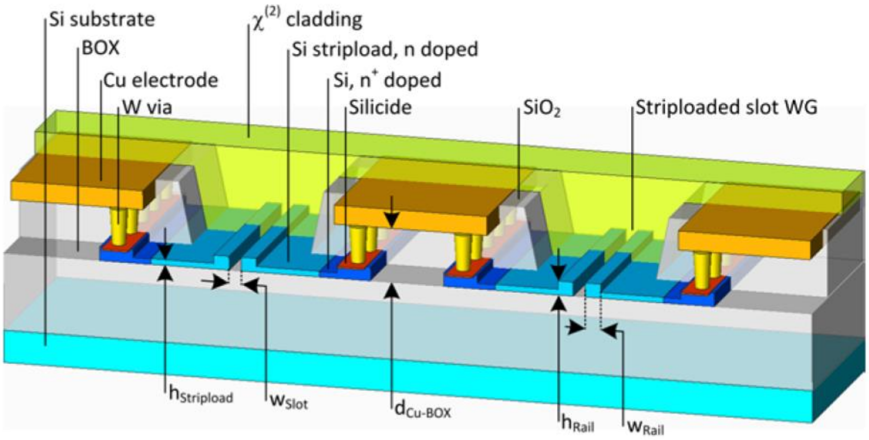


Figure 23. Detailed cross section of MZM as implemented, showing two phase modulators with striploaded slot WGs, filled with nonlinear cladding; not to scale. Rails are connected to ground-signal-ground electrodes by tungsten vias, a silicide layer and the Si striploads. This electrode arrangement allows crossings of optical WGs and electrical transmission lines. Furthermore, it corresponds to the first part of standard metal stacks as known from CMOS technology. Figure source: [1].

A **data generation experiment at 28 GBd using QPSK and 16QAM reaching 112 Gbit/s** confirmed that this device with a length of 1.5 mm performs well within the limits of standard forward error correction (FEC), see **Figure 24**. The polymer produced by GigOptix called M3 has been used in this experiment.

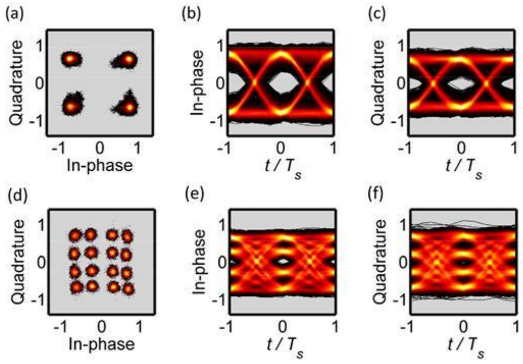


Figure 24. Data generation on a single channel and polarization with SOH IQ modulator at 28 GBd detected using post-equalization with 19-taps. Error free operation is measured and displayed in (a) constellation and (b, c) eye diagrams. (d) Constellation and (b, c) eye diagrams as observed when employing an 8-tap (1 tap per symbol) pre-emphasis at the transmitter, and no equalization at the receiver. The BER is 1.2×10^{-3}, and the EVM is 10.3%. Figure source: [1].

Energy efficiency: Switching to a new, experimental polymer improved the voltage-length product considerable and is a nice example illustrating the SOH concept. “Simply” find a new cladding and a device can be considerably improved, whereas pure SOI modulators require iterative optimization. The resulting low voltage length product allows ultra-low drive voltages [11].

Comb line generation is another task well suited to SOH MZMs, due to their low drive voltages. These frequency combs can be used to create OFDM signals all-optically on-chip. An intermediate step to verify was to create a comb with a larger spacing (and incidentally generating a comb with properties of interest to SELEX) to do wavelength division multiplexing (WDM). The next figure illustrates that a data signal of 784 Gbit/s can be generated as follows:
(a) Use an SOH dual-drive MZM of 2 mm length operated at 40 GHz to create a frequency comb with 40 GHz spacing.
(b) Encode with an LN modulator the same 28 GBd QPSK signal on each carrier.
(c) Separate into even and odd channels, and decorrelate these channels.
(d) Appling an polarization multiplexing.
(e) Receive using an optical modulation analyzer (OMA).

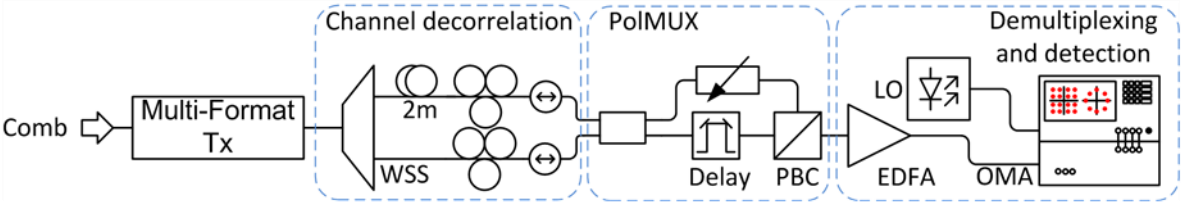


Figure 25. Data transmission setup after generation of comb with SOH MZM: Each comb line is modulated with a 28 GBd QPSK signal. Even and odd channels are separated with a wavelength-selective switch (WSS) to decorrelate neighboring channels. Both data streams are merged and are polarization multiplexed (PolMUX). After amplification, the channels are demultiplexed and detected by an optical modulation analyzer (OMA) and a tunable laser acting as a local oscillator (LO). Figure source: [4]

The viability of using an SOH comb line generator for WDM is proven in the next figure, which shows that each channel can be transmitted with an EVM within the limits of standard FEC.

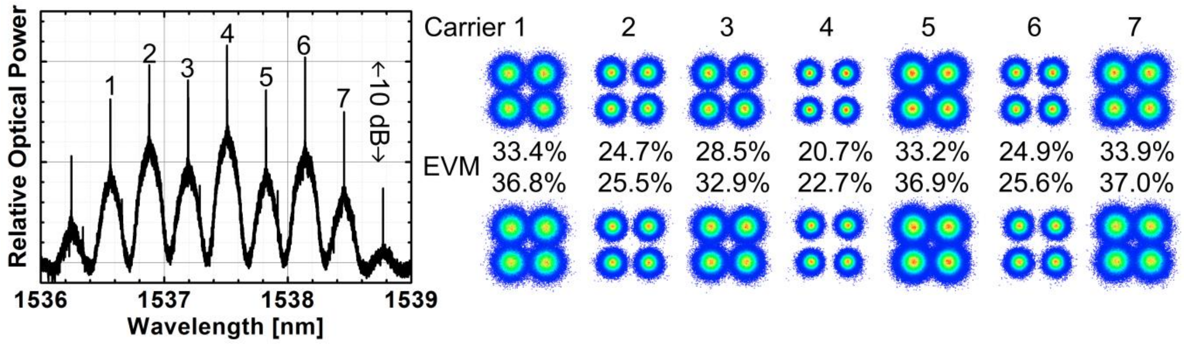
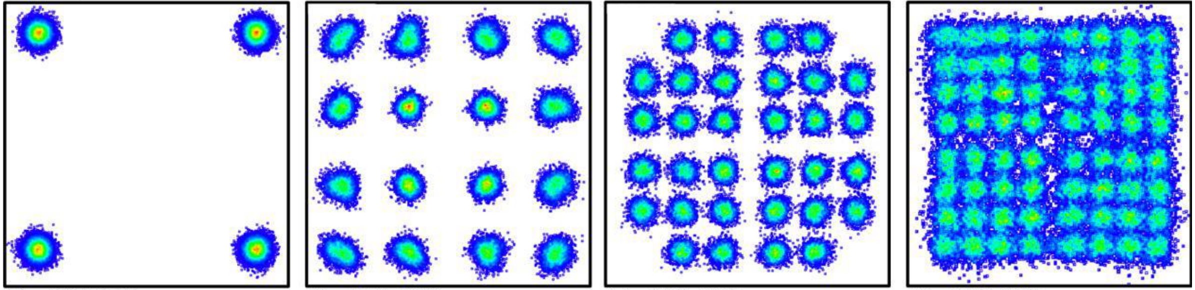


Figure 26. Frequency comb generated by SOH modulator to do WDM using a LN modulator: Data transmission of 784 Gbit/s using QPSK signals on 7 carriers generated by an integrated SOH comb source. Comb spectrum (left) and constellation diagrams for all channels and both polarization are depicted along with measured EVM values. BER below hard-decision threshold are achieved for all signals. Figure source: [4]

The characterization of SOH modulators together with design and simulation generated numerous publications and also prompted KIT to start 2 patent applications focusing on increasing modulation speed by enhancing the modulator's RC constant. The applications are listed here:
'Electro-optical device and method for processing an optical signal, EU,' L. Alloatti, J. Leuthold, W. Freude, C. Koos, D. Korn, and R. Palmer, EP 11003562.3-1228 (2012).
'Electro-optical device and method for processing an optical signal, USA,' L. Alloatti, J. Leuthold, W. Freude, C. Koos, D. Korn, and R. Palmer, U.S.A. 13/460,395 (2012).

Benchmarking studies were extended to real experimental measurements using research prototypes developed under the FP7 project GALACTICO as a reference. A number of GaAs chips provided by the GALACTICO consortium were measured at KIT facilities by **KIT and AIT** researchers to compare their performance with the SOFI modulators. A 3 dB bandwidth of about 32 GHz and constellation diagrams for up to 64QAM modulation at 25 GBd were obtained. Although GaAs devices delivered better results in terms of modulation quality, it is hard to draw conclusions without defining the desired balance with other important devices characteristics, such as foot print and integrability with further functionality on chip (electronics, making arrays). This will require further study outside the SOFI project.



(a) EVM: 6.1%
BER (calculated): < 10^{-18}
BER (measured): error-free

(b) EVM: 7.0%
BER (calculated): ~ 10^{-6}
BER (measured): < $8\cdot10^{-8}$

(c) EVM: 6.3%
BER (calculated): ~ $5\cdot10^{-5}$

(d) EVM: 6.9%
BER (calculated): ~ $1.1\cdot10^{-2}$

Figure 27. Constellation diagrams generated by KIT and AIT with the GALACTICO GaAs IQ modulators. Figure source: [12].

3.8 Driver solution for SOH modulators

GigOptix-Helix AG, a leading fabless supplier of semiconductor components for optical interconnects and CE applications, is a wholly owned subsidiary of GigOptix, Inc (GigOptix), which is serving the wider market of high speed data streaming and telecommunications with a broad offering of semiconductor and optical components.

GigOptix has developed and produces Telcordia proven electro-optical polymer materials which GigOptix used to develop optical modulators addressing all relevant applications in optical transport, including DPSK, RZ-DQPSK, DP-QPSK and 16QAM with speed up to 100 Gbit/s with OOK and 200 Gbit/s with 16QAM. GigOptix-Helix focuses on chipset for optical interconnect with single channel, quad channels and twelve channels VCSEL drivers and TIA w post amp with channel speed up to 28 Gbit/s and are currently used mainly in MMF optical links for datacentres. The receiver arrays have been recently massively introduced in 40 Gbit/s ER and LR links in response to the request from the market for higher level of integration and power dissipation reduction.

The SOFI project aims to implement a silicon-organic hybrid platform which allows for very compact modulators capable of high speed operations and that can be operated in linear mode. These features make the SOFI modulators of potential great interest to GigOptix for standalone use into TOSAs for metro and client side links. Moreover, the possibility of monolithic CMOS integration of the driving electronics with the modulator may make the SOH approach suitable for deployment of EO systems in CE, an area in which GigOptix-Helix in particular is already active.

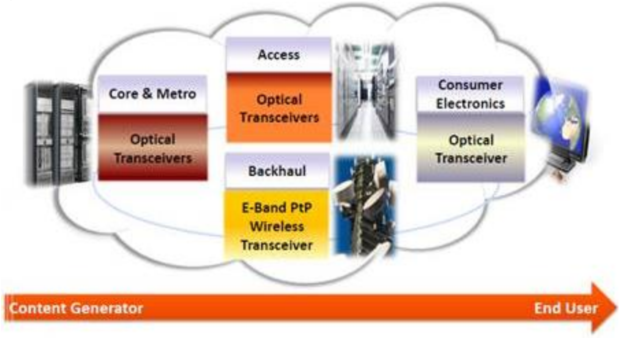


Figure 28. Applications space for GigOptix products.

GigOptix is present in the target applications space with the following optics related products:

- Drivers for EO modulators. Single channel to 4 channels, bit rate per channel up to 32 Gbit/s. SMT, GPPO or coplanar interfaces. Used in 10G to 400G optical transport transmitters.
- MZ modulators. Single and nested MZ modulators, also dual polarization. Used in DPSK, RZ-DQPSK, DP-QPSK and 16QAM with speed up to 100 Gbit/s with OOK and 200 Gbit/s with 16QAM.
- TIAs for coherent receivers. Linear, dual channel, integrated VGA stage with PLD, TIA gain and BW control. Up to 32 Gbit/s per channel. Used in 100G and above coherent receivers.
- VCSEL drivers. Single channel, quad channels, twelve channels with speed up to 28 Gbit/s per channel. Used in transmitter side of optical interconnects.
- Limiting TIA Arrays with post-amp. Single channel, quad channels, twelve channels with speed up to 28 Gbit/s. Used in receiver side of optical interconnects and receivers for client side optical interfaces.
- Specialized TIAs for 3D cameras.

Within the continuous efforts to ever increase networks capacity and speed, the following trends have been identified:

- Long Haul Optical Transport. The increase in capacity and speed is a primary value and accelerated innovation is pursued in some cases at the expense of integration and cost. This approach is justified by the relatively small volumes (10Ks/Y units for the highest speed optical transport interfaces at any given time) and the benefit OEMs have by releasing to the market new products – since this somewhat drives CAPEX on the operators side.
- METRO. Due to the significantly larger volumes with respect to LH/ULH, focus is on the most cost effective solutions, which includes consideration of small foot print and low power dissipation. The increase in performance is achieved through optimization of technology which had become legacy in LH/ULH or adapted from other application areas.

GigOptix worked on the study for an integrated driver. In a first step the SiGe and CMOS technologies were compared based on the transit frequency f_t. The required transit frequency for a 25 Gbit/s driver is above 200 GHz. The slowest BiCMOS technology which fulfills the requirements is a 120 nm BiCMOS process. For the CMOS-only case, a 40 nm technology has to be chosen.
The BiCMOS process has lower mask costs (~300 k$), but higher variable costs per chip, while the CMOS process has much higher mask costs (~2 M$), but lower variable costs per chip.

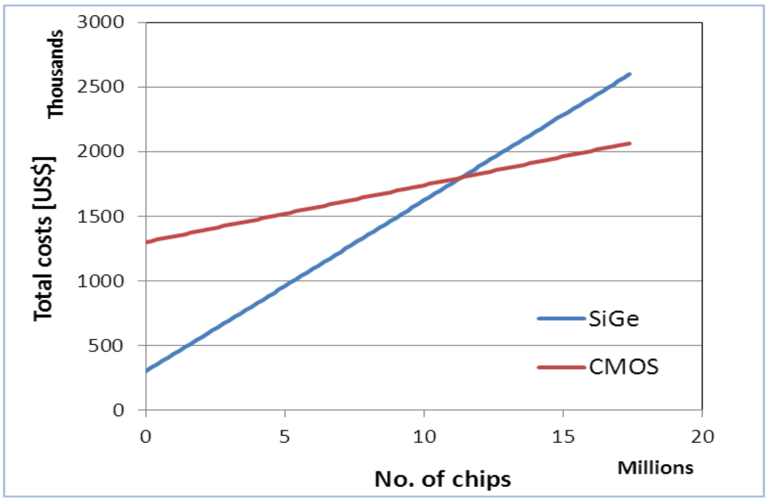


Figure 29. Comparison of the total costs for a certain number of produced chips.

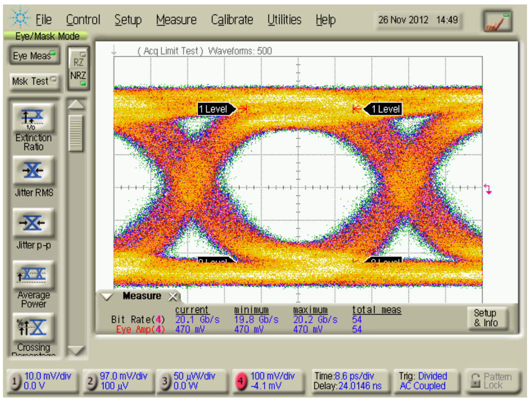
From a cost perspective, SiGe is the better suited technology if less than 10 Mio chips are sold.
Furthermore, the 120 nm BiCMOS process can operate with higher supply voltages than the 40 nm CMOS process. A higher supply voltage (around 3.3 V) enables higher swing sizes.

In order to test the capability to drive a modulator with a SiGe driver, GO worked on an evaluation board. For the evaluation board, a prototype trans-impedance amplifier (TIA) with integrated limiting amplifier from GO has been used. The TIA has normally a current input and is directly bonded to a photo diode (PD). The evaluation board was modified, so that a single ended electrical signal can be fed to the TIA. Because the chip has a very high transimpedance, the electrical signal has to be attenuated between the pattern generator and the board.

Figure 30. Evaluation board for the 25 Gbit/s driver with electrical input and electrical output.

The chip has an I2C interface. The main settings of the chip can be controlled from a PC with a GUI, these settings include the output swing and pre-emphasis.

GO measured output swings up to 600mV. The eye is not fully open. The measured jitter is mainly limited by the measurement setup. The evaluation board has been shipped to KIT and KIT verified the electrical performance and were able to drive a polymer modulator.



(Acq Limit Test) Waveforms: 500

	current	minimum	maximum	total meas
Bit Rate(4)	20.1 Gb/s	19.8 Gb/s	20.2 Gb/s	54
Eye Amp(4)	470 mV	470 mV	470 mV	54

1 10.0 mV/div 0.0 V
2 97.0 mV/div 100 µV
3 50 µW/div 0.0 W
4 100 mV/div -4.1 mV
Time: 8.6 ps/div Delay: 24.0146 ns
Trig: Divided AC Coupled

Figure 31. Measured single ended eye diagram at 20 Gbit/s. The measurement was limited by the measurement setup and its limited jitter performance.

In the meantime, an improved version of this prototype chip was designed. The new version should have more bandwidth, improved pre-emphasis and channel inversion. The device was successfully characterized by GigOptix.
On SOFI3 run, KIT designed an array of IQ modulators with 4 QPSK channels. The electrodes have the same spacing as our 12 channel prototype chip. The aim is to directly bond the driver chip to the MZMs and drive all 8 simultaneously at 25 Gbit/s or 12.5 Gbit/s. In order to do this, GO started with the design of a dedicated EVB.

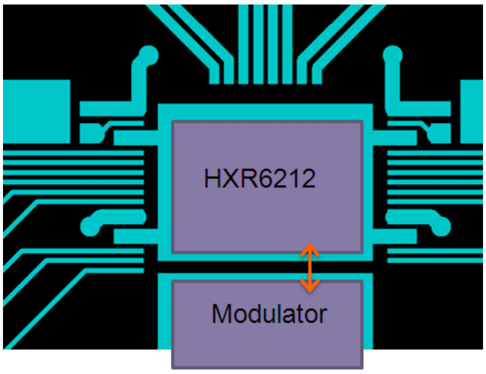
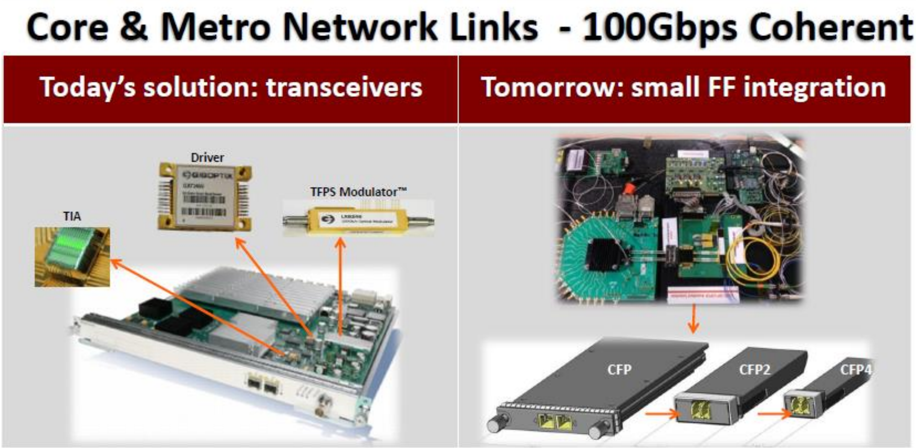


Figure 32. Sketch of the dedicated PCB to drive the 8 MZM


Core & Metro Network Links - 100Gbps Coherent

Today's solution: transceivers

Tomorrow: small FF integration

Figure 33. Integration Trend for METRO optical interfaces.

In particular METRO applications are calling for DP-QPSK modulators with small footprint, low Vpi, BW capable of 28 GBd to 32 GBd. Possibility to integrate the drivers with the modulator is considered a plus. In the future, to extend further the capacity, there may be need to support complex modulation formats, like 16QAM also, which will call for modulators capable of linear operations. All the above requirements are among the targets of SOFI and supporting the interest at GigOptix in the SOFI project.

Another relevant use case for the components and technologies developed in SOFI is the emerging need for high speed links for the campus and very large datacenters. Until recently the size of datacenters was such that the vast majority of links was below 30 m with very few links of 100 m and above and maximum length of 300 m. Such requirements allowed for the implementation of optical links for datacenters using MMF and 850 nm VCSELs. Due to the great increase in size of datacenters and the introduction of new network architectures to improve the speed and reliability of the datacenters operations, the requirement for 1 km to 2 km links has recently emerged. Current implementations for such links are based on OOK and CWDM, however such solutions are offering between 40 Gbit/s and 100 Gbit/s with a path to 400G that can be achieved only increasing the complexity of the optics. Following successful commercial introduction of ultrafast DAC it is being proposed to use multilevel amplitude signaling (8PAM or 16PAM) to increase the capacity for this class of optical links. This application requires the MZ modulator to operate in linear mode driven by DSP generated signals. The electronic needed to generate the transmitted signal would include high complexity large real estate mixed signal circuitry with significant size/cost benefits coming from the monolithic CMOS integration of the electronics with the optical modulators, one of the main investigation areas of the SOFI project.

Very large volume deployment of optical links in consumer electronics has not happened yet but there are ever growing indications it will happen soon. 10 Gbit/s and 20 Gbit/s serial links to connect the PC to external peripherals have been already proposed by leading manufacturers (APPLE/INTEL, Thunderbold) and the extension of existing PC interfaces to support optical physical layer (USB and PCIe) is ongoing. For these applications, for which annual volumes of tenths of millions devices per year are likely and cost will need to reach the level of a few $s per port, monolithic integration of CMOS electronics with the E/O components looks attractive.

To summarize, GigOptix interest related to the SOFI project is manifold and relates to a number of the market GigOptix is active in. The most relevant aspects in SOFI as far as GigOptix is concerned are:

- The development of a technology yielding very compact and complex modulators capable of high speed operations and that can be operated in linear mode.
- The monolithic CMOS integration of the transmitter electronics with the modulator.

4 Potential impact

It is now widely recognized that reducing the level of global energy consumption is of paramount importance and must be addressed with urgency. Silicon photonic technologies and more specifically silicon hybrid technologies offer significant advantages towards achieving this goal. Currently, the total energy required to power the Internet, including data centers, network nodes and user terminals, amounts to about 4% of today’s electricity generation. With Internet traffic doubling every 18 months, a 64-fold increase in the Internet’s total power consumption is expected in less than 10 years, and this would require a more than doubling of the required total capacity for global electricity generation.
In accordance to the above, the EU’s climate and energy policy has set a target for cutting energy consumption by 20% of projected 2020 levels by improving energy efficiency**.** Information and Communication Technologies (ICT) play a key role in the roadmap strategy towards reduction of carbon footprint in assisting the performance of other sectors in the world economy. However, in recent years the carbon emissions of ICT itself have rapidly increased due to the associated growth of internet traffic owing to social networking and video services which at the end of 2012 will account for more than half of the global internet traffic. Despite the fact that, at the current capacity levels telecommunication networks power consumption is at moderate values, the forecasted traffic growth predicts that in the upcoming years it will become a major problem for the operators strategic planning.

The studies of **AIT** show that SOH will be a competitive modulator technology that is capable to meet the specifications of new generation long haul and access networks, which will require high speed modulators with ultra-high bandwidth, i.e., modulators showing superior performance with respect to commercial available technologies (e.g LiNbO3), low power consumption and at reduced cost. Extended analyses and a number of simulations show that a total network energy lowering in the order of 22% is achievable using the SOFI devices leading to new more efficient subsystems and meeting the EU requirements for greener technologies.

From **IMEC**’s point of view, the direct impact of the project is a significant enhancement of the technology platform: The incorporation of high-quality exposed slot waveguides in a CMOS-compatible silicon photonics platform is not only relevant for high-speed and low-power modulators, but also for sensors. This can be a key differentiator of silicon photonics.
As one of the technology providers for ePIXfab, IMEC has also recently started to offer the full platform (passives + modulators + detectors) in multi-project wafer (MPW) runs. The SOFI-specific modules are not yet a part of that

offering, but if there is a clear demand for back-end opening, IMEC will consider to integrate this as a standard module in the platform. This injects the SOFI technology into the silicon photonics supply chain in Europe.

Within the SOFI project, silicon-organic hybrid modulation at a high speed has been demonstrated for the first time with organic crystals from **Rainbow Photonics**. This opens up a new opportunity for organic crystals to replace poled polymers in SOH applications where high long-term stability, resistance to high optical powers and temperatures, and parallelism is required, (for polymers it is difficult to pole several on-chip devices simultaneously). This is not only interesting for high-speed electro-optic modulation, but also other applications where high-speed $\chi(2)$ nonlinear optical functionality is required. For example, organic electro-optic crystals are very promising for THz-wave generation in a broad range 0.1–20 THz and above, presently used exclusively in a bulk form by several research groups worldwide and in commercial THz sources offered by Rainbow Photonics. The integrated SOH platform could offer more than three orders of magnitude better optical-to-THz conversion efficiencies compared to present (bulk) applications, considerably reduced size compatible with applications such as endoscopy and THz micro-testing, as well as new functionalities offered by silicon structures.

Many commercial products prove that it is possible to design chromophores hosted polymers for durable, resilient products. In the SOFI project the material M3 of GigOptix Inc. has been used to produce SOH modulators. This is the very same material employed in Telecordia certified modulators sold by GigOptix. Also new polymers/chromophores can be further enhanced. Demand for high performing, energy efficient modulators will drive these developments in chemistry.

The potential applications from the output of the project envisaged by **SELEX ES** rely on both military and civil fields that are mainly focused on the improvement of advanced generation of Multifunction Phased Array Radars (M-PAR). The SOH modulator developed in SOFI is a useful building block to be used within already existing products as well as for future RADAR architecture.
It has been identified as a potential replacement for the modulators based on other technologies (such as $LiNbO_3$, GaAs, GaN, Si EAM) in both analogue and digital optical links, with the advantages of increased bandwidth, power efficiency, scalability, and reduced volume and costs.

In SOFI, **GigOptix-Helix** performed a study for an optimized driver for the SOFI modulator. Also, the feasibility of driving a SOFI modulator with an integrated Silicon-Germanium (SiGe) driver was proved. This result is of particular relevance since the possibility to drive the SOFI modulator with SiGe drivers may allow the deployment of the SOFI modulators even in cases in which the volumes do not justify the investment in the monolithic integration of the electronics with the modulator. Also the possibility to use compact low power SiGe drivers still support extremely compact low power multi-channel TOSAs in which the SOFI modulators shall provide a distinct advantage with respect to competing technologies.
Support in the design activities and process developments for the SOFI modulator. It is worth mentioning that the material supplier by GigOptix-Helix allowed an early validation of the SOFI concept and proved to be well suited for the realization of complex optical components on silicon optical waveguides, like the SOFI IQ modulator.

The SOFI project helped to establish that SOH modulators and SOH photonic integrated circuits support advanced modulation formats, provide exceptionally high bandwidth, also because devices can be made especially short thanks to very low $V_\pi L$ products. Moreover by using modulators of 1 mm length this modulation efficiency translates into the most energy efficient high-speed Mach-Zehnder modulators to-date, which are not bound to a specific, hard to control wavelength.

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5 Use and dissemination of foreground – Section A (dissemination measures, scientific publications)

This chapter is also implemented as deliverable D6.7, D6.8, D6.10 and reproduced here to make this a standalone document.

A1: LIST OF SCIENTIFIC (PEER REVIEWED) PUBLICATIONS, STARTING WITH THE MOST IMPORTANT ONES

NO.	Title	Main author	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Year of publication	Relevant pages	Permanent identifiers[1] (if available)	Is/Will open access[2] provided to this publication?
1	*'Silicon-organic hybrid (SOH) IQ modulator using the linear electro-optic effect for transmitting 16QAM at 112 Gbit/s'*	*KIT*	*Optics Express*				*2013*		doi: 10.1364/OE.21.013219	yes
2	Low Power Mach-Zehnder Modulator in Silicon-Organic Hybrid Technology	*KIT*	IEEE Photonic Technol. Lett.;				2013		doi: 10.1109/LPT. 2013.2260858	
3	'Silicon-Organic Hybrid MZI Modulator Generating OOK, BPSK and 8-ASK Signals for up to 84 Gbit/s'	*KIT*	IEEE Photonics J.				2013		doi: 10.1109/JPHOT.2013.2258142	
4	'Low-Loss Silicon Strip-to-Slot Mode Converters,'	*KIT*	IEEE Photonics J.				2013		doi: 10.1109/JPHOT.2013.2239283	
5	'Second-order nonlinear silicon-organic hybrid waveguide	*KIT*	Optics Express				2012		dx.doi.org/10.1364/OE.20.020506	yes
6	Silicon-organic hybrid phase	*KIT*	Optics Express				2012		dx.doi.org/10.1364/OE.20.015359	yes

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[1] A permanent identifier should be a persistent link to the published version full text if open access or abstract if article is pay per view) or to the final manuscript accepted for publication (link to article in repository).

[2] Open Access is defined as free of charge access for anyone via Internet. Please answer "yes" if the open access to the publication is already established and also if the embargo period for open access is not yet over but you intend to establish open access afterwards.

	shifter based on a slot waveguide with a liquid-crystal cladding									
7	42.7 Gbit/s electro-optic modulator in silicon technology	*KIT*	Optics Express				2011		doi:10.1364/OE.19.011841	yes
8	Monolithic GaAs Electro-Optic IQ Modulator Demonstrated at 150 Gbit/s with 64 QAM	*KIT*	Lightwave Technology				2013		10.1109/JLT.2013.2278381	yes

A2: **LIST OF DISSEMINATION ACTIVITIES**

NO.	Type of activities[3]	Main leader	Title	Date/ Period	Place	Type of audience[4]	Size of audience	Countries addressed
1	*Conference*	*KIT*	*ECOC*	*2013*	*London, UK*	*scientific*	*>1000*	international
2	*Conference*	*KIT*	*CLEO Europe*	*2013*	*Munich, Germany*	*scientific*	*>1000*	international
3	*Conference*	*KIT*	*CLEO US*	*2013*	*San Jose, USA*	*scientific*	*>1000*	international
4	*Conference*	*KIT*	*OFC*	*2013*	*Los Angeles,USA*	*scientific*	*>1000*	international
5	*Conference*	*KIT*	*ECOC*	*2012*	*Europe*	*scientific*	*>1000*	international
6	*Conference*	*KIT*	*CLEO US*	*2012*	*San Jose, USA*	*scientific*	*>1000*	international
7	*Conference*	*KIT*	*OFC*	*2012*	*US*	*scientific*	*>1000*	international
5	*Conference*	*KIT*	*ECOC*	*2011*	*Europe*	*scientific*	*>1000*	international
6	*Conference*	*KIT*	*CLEO US*	*2011*	*Baltimore, USA*	*scientific*	*>1000*	international

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[3] A drop down list allows choosing the dissemination activity: publications, conferences, workshops, web, press releases, flyers, articles published in the popular press, videos, media briefings, presentations, exhibitions, thesis, interviews, films, TV clips, posters, Other.

[4] A drop down list allows choosing the type of public: Scientific Community (higher education, Research), Industry, Civil Society, Policy makers, Medias, Other ('multiple choices' is possible).

7	*Conference*	*KIT*	*OFC*	*2011*	*USA*	*scientific*	>1000	international
8	*Exhibition*	*GO*	*ECOC*	*2012*	*Amsterdam,The Netherlands*	*Industry*	>1000	international
9	*Exhibition*	*GO*	*OFC*	*2013*	*Anaheim, USA*	*Industry*	>1000	international
10	*Exhibition*	*GO*	*ECOC*	*2011*	*Europe*	*Industry*	>1000	international
11	*Exhibition*	*GO*	*OFC*	*2012*	*USA*	*Industry*	>1000	international
12	*Exhibition*	*GO*	*ECOC*	*2010*	*Europe*	*Industry*	>1000	international
13	*Exhibition*	*GO*	*OFC*	*2011*	*USA*	*Industry*	>1000	international
14	*Exhibition*	*RB*	*SPIE Photonics West*	*2013*	*San. Francisco, USA*	*insustry*	>1000	International
15	*Exhibition*	*RB*	*Laser World of Photonics*	*2013*	*Munich, Germany*	*Industry*	>1000	International
16	*Conference*	*KIT*	*Frontiers in Optics*	*2013*	*Orlando, FL, USA*	*Scientific*	>1000	International
17	*Workshop*	*AIT*	*ICTON*	*2013*	*Cartagena, Spain*	*Scientific*	>1000	International
18	*Spring School*	*AIT*	*Europhotonics*	*2013*	*Pforzheim, Germany*	*Scientific*	>150	International
19	*Conference*	*AIT*	*Micro&Nano*	*2012*	*Heraklion, Greece*	*Scientific*	>300	International
20	*Conference*	*KIT*	*ICTON*	*2012*	*Coventry, UK*	*Scientific*	>1000	International
21	*Workshop*	*AIT*	*ICTON*	*2012*	*Coventry, UK*	*Scientific*	>1000	International
22	*Conference*	*AIT*	*ICTON*	*2011*	*Stockholm, Sweden*	*Scientific*	>1000	International
23	*Conference*	*AIT*	*IEEE-ICT*	*2011*	*Cyprus*	*Scientific*	>1000	International
24	*Scientific Symposium*	*AIT*	*Niki Award2012*	*2012*	*Athens, Greece*	*Scientific*	>100	International
25	*Seminar*	*AIT*	*Internal presentation*	*2011*	*Athens, Greece*	*Scientific*	>1000	National

All partners of the SOFI consortium have been committed to mobilize their contacts in the international research society and industry to promote the project results.

The participation in conferences, workshops and EU events not only falls in the project scope but it is one of the main project objectives.

Scientific contributions have and will continue to be submitted, throughout the project lifetime, for publication to journals/conferences, provided that they will enhance project visibility and release useful conclusions to the telecom community.

The dissemination plan includes the creation and maintenance of a professional project website containing all public information and facilitating contacts and exchanges with other research and industrial initiatives on the relevant topics. This consortium WEB site was created and is maintained by KIT with inputs from all partners.

SOFI project promotion events

SOFI project has organized the following promotion events:

a. A Special Session on “Silicon Photonics Based Components”, co-located with ICTON 2012, held in Coventry, England, on July 2 – 5, 2012.
b. An ECOC 2012 Workshop on “Silicon Hybrid Photonics” held in Amsterdam, Netherlands, on September 16, 2012
c. A joint SOFI/NAVOLCHI Special Session on "CMOS Fabrication-Based Photonic Technologies for Communications" co-located with ICTON 2013, held in Cartagena, Spain on June 23-27, 2013.

The purpose of these events was to present the outcomes of the undertaken research activities on Silicon photonics components and systems and to stimulate useful discussions among experts in this topic on the new technology trends, achievements and solutions.

Also SOFI participated in the Erasmus Mundus Spring School 2013, held in Hohenwart Forum, Germany on April 08-10, 2013 and organized by the SOFI partner KIT.

The following paragraphs provide details on the structure of the organized events and evaluate their outcome and impact to the SOFI project.

Special Session on Silicon Photonics Based Components at ICTON 2012

This promotion event has been organized by the SOFI partners AIT and KIT as a full half day session on the 5th of July 2012. The main goal of this event was to solicit invited and contributed presentations on the hot topic of silicon photonics based components for telecommunications and high performance computing applications.

The final structure of the session program is shown below:

	SESSION Th.A5 (9:30 – 11:40) **SOFI**
9:30	**Th.A5.1** Chip-to-chip plasmonic interconnects and the activities of EU project NAVOLCHI (***Invited***) ***A. Melikyan***, *M. Sommer, A. Muslija, M. Kohl, S. Muehlbrandt, A. Mishra, V. Calzadilla, Y. Justo, J.P. Martínez-Pastor, I. Tomkos, A. Scandurra, D. Van Thourhout, Z. Hens, M. Smit, W. Freude, C. Koos, J. Leuthold*
9:50	**Th.A5.2** Surface plasmon-polariton amplifiers (***Invited***) ***I. Suárez***, *P. Rodriguez-Cantó, R. Abargues, J. Martinez-Pastor, E.P. Fitrakis, I. Tomkos*
10:10	**Th.A5.3** Low energy routing platforms for optical interconnects using active plasmonics integrated with silicon photonics (***Invited***) ***K. Vyrsokinos***, *S. Papaioannou, N. Pleros, D. Kalavrouziotis, G. Giannoulis, D. Apostolopoulos, H. Avramopoulos, J-C. Weeber, K. Hassan, L. Markey, A. Dereux, A. Kumar, S.I. Bozhevolnyi, M. Baus*
10:30	**Th.A5.4** Broadband and picosecond intraband absorption in lead based colloidal quantum dots (***Invited***) *B. De Geyter, P. Geiregat, D. Van Thourhout, Yunan Gao, S.T. Cate, A.J. Houtepen, J.M. Schins, L.D.A. Siebbeles,* ***Z. Hens***
10:50	**Th.A5.5** Silicon-organic hybrid fabrication platform for integrated circuits (***Invited***) ***D. Korn***, *L. Alloatti, M. Lauermann, J. Pfeifle, R. Palmer, P.C. Schindler, W. Freude, C. Koos, J. Leuthold, Hui Yu, W. Bogaerts, K. Komorowska, R. Baets, J. Van Campenhout, P. Verheyen, J. Wouters, M. Moelants, P. Absil, A. Secchi, M. Dispenza, S. Wehrli, M. Bossard, P. Zakynthinos, I. Tomkos*
11:10	**Th.A5.6** Exploiting photosensitive As_2S_3chalcogenide glass in photonic integrated circuits ***S. Grillanda***, *A. Canciamilla, F. Morichetti, Juejun Hu, V. Singh, A. Agarwal, L.C. Kimerling, A. Melloni*
11:25	**Th.A5.7** Towards plasmonic lasers for optical interconnects *V. Dolores-Calzadilla, A. Fiore, M.K. Smit*

The speakers identified the great potentials of the silicon photonics technology as it is based on the mature low-cost CMOS fabrication process technology, thus allowing for the convergence of electronics with optics on the same platform. This was highlighted in many presentations, showing the requirements and fabrication processes of platforms for integrated circuit systems. Moreover, the session presented the new technology advancements, like the silicon-organic hybrid technology developed within the framework of SOFI, that enable the creation of new components with functionalities that so far are not available in silicon and achievable bit-rates beyond 100 Gbit/s.

The participation in this session was exceeded 40 people; (no official participation data per session are available by the organizers). The session closed with a 15min open discussion among the invited presenters in which all highlighted the future potential of silicon photonics mainly towards: a) the creation of low energy consumption and high bandwidth components and b) integrated system solutions primarily for applications in data interconnects.

Workshop on "Silicon Hybrid Photonics" at ECOC 2012
The most significant promotion event for SOFI project was organized at ECOC 2012 held on Amsterdam, Netherlands on September 16-20, 2012. ECOC is the largest conference on photonic technologies, system and network applications in Europe and the second largest in the world attracting over 1000 researchers to present their work and be updated on the latest research achievements. The first day of the conference is devoted to limited number of specialized and targeted half day workshops.

The SOFI workshop on Silicon Hybrid Photonics was organized by the SOFI partner IMEC in collaboration with Rainbow Photonics partner and Ghent University. A list of the presentations in this workshop is provided in the table below:

Sunday, 16 September • 09:00–12:30 **Room B** **WS2: Silicon Hybrid Photonics**
III-V on Silicon Integration for Active-passive Photonic Integrated Circuits *John Bowers,* *University of California, Santa Barbara, USA*
Silicon-organic Hybrids for Modulators and Nonlinear Applications *Juerg Leuthold,* *Karlsruhe Institute of Technology, Germany*
Monolithic Optical Isolators for Silicon Microphotonics *Lionel Kimerling,* *Massachusetts Institute of Technology, USA*
SiGeSn Photodiodes with Tunable Band Gaps Integrated Directly on Si and Ge Platforms *John Kouvetakis,* *Arizona State University, USA*
New Trends in Carbon Nanotubes Based Photonics on Silicon *Nicolas Izard,* *Université Paris Sud, France*
Bringing New Materials in a Silicon Fab: A Good Idea? *Peter Verheyen,* *IMEC, Belgium*

The event hosted a total of six 30 minute presentations and allocated another 30 minutes at the end for discussions and questions between the audience and panel of presenters. It is noted that half of the presentations were provided by researchers in European institutes and the half by researcher form renowned institutes in the USA. All presenters are among the worlds' experts in the field of silicon photonics, and as a result the latest research trends in the field were summarized in this workshop.

The presenters identified silicon photonics as one of the most promising technologies for large-scale photonic integration. They have highlighted the new capabilities that are offered for the development of high index contrast, compact and complex passive circuits based on CMOS manufacturing technology today. However, it was commonly agreed that since silicon on its own is impossible to be a material for active optical elements (e.g. modulators, switches, detectors, and especially light sources), the hybridization of the silicon platform with novel materials is strongly required. The key though to successful hybrid platform is the identification of solutions that does not compromise the advantages of silicon technology. Many presentations in the workshop have focused on the properties, the advantages and the disadvantages of different materials that have examined by various research groups but also on the integration approaches and the related technical challenges for a variety of on-chip optical functions. The final discussions between the audience and the panel were concentrated mainly on the optimum choice of materials for improved optical performance, the most promising solutions for the integrated silicon platforms and functionality of the integrated systems that can be achieved according to the selection of the material and the platform.

It is noted that the workshop have attracted more than 120 attendees, including a large number of renowned researchers in the field from around the world that have actively contributed to the commenting of the presented work and the final panel discussions.

Special Session on CMOS Fabrication-Based Photonic Technologies for Communications at ICTON 2013
The last promotion event was a joint activity between the projects SOFI and ICT FP7-NAVOLCHI and organised by the partners AIT and KIT. The main goal of this event was to show the latest research outcomes of both projects before their completion and highlight the future potentials and capabilities of the developed technologies. The primary foci of this session talks was on the plasmonic-silicon and organic-silicon based components for communication applications.

The final structure of the session program is shown below:

	SESSION We.D6 **NAVOLCHI/SOFI** **Chair: Ioannis Tomkos**
9:30	**We.D6.1** Waveguide-coupled nanolasers in III-V membranes on silicon (Invited) ***V. Dolores-Calzadilla, D. Heiss, A. Fiore, M. Smi***
9:50	**We.D6.2** Optical properties of SOI waveguides functionalized with close-packed quantum dot films (Invited) ***Z. Hens, A. Omari, P. Geiregat, D. Van Thourhout***
10:10	**We.D6.3** Light coupling from active polymer layers to hybrid dielectric-plasmonic waveguides (Invited) ***I. Suárez, E.P. Fitrakis, H. Gordillo, P. Rodriguez-Cantó, R. Abargues, I. Tomkos, J. Martinez-Pastor***
10:30	**We.D6.4** Low energy routing platforms for optical interconnects using active plasmonics integrated with silicon photonics (Invited) *K. Vyrsokinos, S. Papaioannou, D. Kalavrouziotis, F. Zacharatos, L. Markey, J-C. Weeber, A. Dereux, A. Kumar, S.I. Bozhevolnyi, M. Waldow, G. Giannoulis, D. Apostolopoulos, T. Tekin, H. Avramopoulos, N. Pleros*

The speakers presented the latest research outcomes on SOI waveguide based systems as well as plasmonic waveguide platforms highlighting the light coupling properties achieved at low energy consumption levels. The event also hosted a presentation from the project PLATON presenting an integrated platform with active plasmonics on silicon photonics.

The participation in this session was exceeded 50 people; (no official participation data per session are available by the organizers). The session closed with a 15min summary of the research achievements in projects SOFI and NAVOLCHI while each speaker identified the future trend of these technologies and their requirements for the creation of functional low-energy systems.

SOFI in Erasmus Mundus Spring School 2013
The Europhonics Erasmus Mundus Spring School is an annual workshop designed to gather together Master students, PhD students and professors and is a privileged moment for exchanging experiences and preparing future careers.
The program consists of talks and courses in selected areas of photonics given by invited researchers. All Europhotonics second year Master students and all PhD students attend the Spring School. The School is also open to other students from across Europe/

SOFI project has offered a general educative presentation to all students attending the Erasmus Mundus Spring School. This spring school was a two and a half day event organized by SOFI partner KIT and included a mixture of presentations on new material and technologies as well as their application in our lives. The spring school program can be found at:
http://ksop.idschools.kit.edu/downloads/EM_Spring_School_2013_Program_final(1).pdf

The SOFI presentation was created in a form of an 1 hour lecture presentation and presented in the spring school event by AIT. This presentation included an introduction to silicon photonics research activities and photonic integration technologies as well the scope and focus of the SOFI project and its major achievements. The SOFI presentation attracted more than 30 students which showed a great interest in silicon photonics technologies with various questions to the AIT speaker.

Figure 1 a) Prof. Uli Lemmer welcomes the spring school attendees, b) snapshot from the oral sessions c) snapshot from the poster session

RB - Latest dissemination activities

Conferences and Symposiums

Rainbow Photonics was present at the following international exhibitions with the company booth, where we were also promoting our work within the SOFI project:

- SPIE Photonics West exhibition, Febr. 4–7 2013 in San Francisco USA
- Laser World of Photonics exhibition, May 13-16 2013 in Munich, Germany

In the reporting period Rainbow Photonics promoted the activities within SOFI in the following papers:

- **'Organic DSTMS crystals for high-field wide bandwidth THz spectroscopy'** (Invited, Keynote Presentation); Peter Günter, Mojca Jazbinsek, Tobias Bach, Blanca Ruiz, Carolina Medrano, SPIE Photonics West (February 2-7, 2013); San Francisco, USA. This presentation promoted organic electro-optic crystals for generation and detection of THz waves, but also their potential for high-speed integrated optics.

- **'Generation of frequency tunable and broadband THz pulses in the frequency range 1-20 THz with organic electro-optic crystals OH1 and DSTMS'** (Oral presentation); Mojca Jazbinsek, Tobias Bach, Blanca Ruiz, Carolina Medrano, Peter Günter; SPIE Photonics West (February 2-7, 2013), San Francisco, USA. Experimental results on frequency tunable THz-wave generation with bulk organic crystals, also mentioning their potential for high-speed integrated optics.

- **'Broadband THz-Wave Generation with Organic Crystals OH1 and DSTMS'**; Mojca Jazbinsek, Blanca Ruiz, Carolina Medrano, Peter Günter; CLEO Europe (May 12-16, 2013), Munich, Germany. Experimental results on ultra-broadband THz-wave generation with bulk organic crystals based on their ultra-fast electro-optic response.

- SOFI partners presented an invited paper to ICTON 2012 (July 2 – 5, 2012, Coventry, UK), **'Silicon organic hybrid fabrication platform for integrated circuits'**; Korn, D.; Alloatti, L.; Lauermann, M.; Pfeifle, J.; Palmer, R.; Schindler, P. C.; Freude, W.; Koos, C.; Leuthold, J.; Yu, H.; Bogaerts, W.; Komorowska, K.; Baets, R.; Van Campenhout, J.; Verheyen, P.; Wouters, J.; Moelants, M.; Absil, P.; Dispenza, M.; Secchi, A.; Jazbinsek, M.; Gunter, P.; Wehrli, S.; Bossard, M.; Zakynthinos, P.; Tomkos, I.;

- One journal paper by KIT, RB and IMEC on hybrid integration of organic crystals in silicon platform is in preparation.

AIT - Latest dissemination activities

Conferences and Symposiums

- ***AIT*** presented a paper at Fifth International Conference on Micro - Nanoelectronics, Nanotechnologies and MEMS "Micro&Nano2012" (October 7-10, 2012, Heraklion, Greece). This work included the results from the simulation studies performed under WP2 on the potentials of the SOFI devices in high speed telecom systems. Paper title and author list: “**Silicon-Organic Hybrid Modulators for High Speed Transmission Systems” , Panagiotis Zakynthinos, Leontios Stampoulidis, Efstratios Kehayas and Ioannis Tomkos**

- **KIT** and **AIT** submitted a successful post-deadline paper to OFC 2013 conference (March 17-21, 2013, LA, USA) presenting the results obtained during the SOFI-GALACTICO experimental activity. Paper title and author list: **“Experimental Demonstration of up to 64-QAM Modulation Formats Using the First High-Speed Monolithic IQ GaAs Electro-optic Modulator”, D. Korn, P. C. Schindler, C. Stamatiadis, M. F. O’Keefe, L. Stampoulidis, R. Schmogrow, P. Zakynthinos, N. Cameron, Y. Zhou, R. G. Walker, E. Kehayas, I. Tomkos, L. Zimmermann, R. Palmer, W. Freude, C. Koos, J. Leuthold**

- **KIT, GO**, **IMEC** and **AIT** partners prepared and submitted an invited paper to OSA’s Annual Meeting, Frontiers in Optics 2013 (October 6-10, 2013, Orlando, FL, USA.). Paper title and author list: **“Nonlinear Nano-Photonics”, W. Freude, L. Alloatti, M. Lauermann1 A. Melikyan, D. Korn, R. Palmer, J. Pfeifle, P. C. Schindler, C. Weimann1 R. Dinu, J. Bolten, T. Wahlbrink, M. Waldow, S. Walheim, P. M. Leufke, S. Ulrich, J. Ye, P. Vincze, H. Hahn, H. Yu, W. Bogaerts, K. Hartinger, V. Brasch, T. Herr, R. Holzwarth, C. Stamatiadis, M. F. O’Keefe, L. Stampoulidis, L. Zimmermann, R. Baets, Th. Schimmel, I. Tomkos, K. Petermann, T. Kippenberg, C. Koos, J. Leuthold**

- SOFI partners submitted an invited paper to ICTON 2012 (July 2 – 5, 2012, Coventry, UK, presenting the project concept, technology and achievements. Paper title and author list: “**Silicon-organic hybrid fabrication platform for integrated circuits”, D. Korn, L. Alloatti, M. Lauermann, J. Pfeifle, R. Palmer, P.C. Schindler, W. Freude, C. Koos, J. Leuthold, Hui Yu, W. Bogaerts, K. Komorowska, R. Baets, J. Van Campenhout, P. Verheyen, J. Wouters, M. Moelants, P. Absil, A. Secchi, M. Dispenza, S. Wehrli, M. Bossard, P. Zakynthinos, I. Tomkos**

Journals

- KIT and AIT partners submitted an invited paper to Journal of Lightwave Technology presenting the results obtained during the SOFI-GALACTICO collaboration experimental activities. Paper title and author list: **“Monolithic GaAs Electro-Optic IQ Modulator Demonstrated at 150 Gbit/s with 64QAM”, P. C. Schindler, D. Korn, C. Stamatiadis, M.F. O’Keefe, L. Stampoulidis, R. Schmogrow, P. Zakynthinos, R. Palmer, N. Cameron, Y. Zhou, R. G. Walker, E. Kehayas, I. Tomkos, L. Zimmermann, K Petermann, W. Freude, C. Koos, and J. Leuthold**.

Other Dissemination Activities

- During a short seminar event, AIT has presented the SOFI technology platform to interested AIT graduate students and researchers.
- AIT organised two conference workshops:
  a) A Special Session on “Silicon Photonics Based Components”, co-located with ICTON 2012, held in Coventry, England, on July 2 – 5, 2012.
  b) A joint Special Session in collaboration with ICT FP7-NAVOLCHI on "CMOS Fabrication-Based Photonic Technologies for Communications" co-located with ICTON 2013, held in Cartagena, Spain on June 23-27, 2013

  More details about these two events are provided in D6.7

- During the “Niki Award 2012” event, AIT’s researchers presented the SOFI project and its achievements to the director of Lawrence Berkeley National Laboratory and to a large number of scientists.
- AIT prepared an extended presentation for the Europhotonics Spring School 2013 (April 8-10, Pforzheim, Germany) organized by *KIT*. More details about this event is provided in D6.7

SELEX - Latest dissemination activities

Conferences and Symposiums

In the reporting period Selex contributed to the following papers:

- SOFI partners presented an invited paper to ICTON 2012 (July 2 – 5, 2012, Coventry, UK), **'Silicon organic hybrid fabrication platform for integrated circuits'**; Korn, D.; Alloatti, L.; Lauermann, M.; Pfeifle, J.; Palmer, R.; Schindler, P. C.; Freude, W.; Koos, C.; Leuthold, J.; Yu, H.; Bogaerts, W.; Komorowska, K.; Baets, R.; Van Campenhout, J.; Verheyen, P.; Wouters, J.; Moelants, M.; Absil, P.; Dispenza, M.; Secchi, A.; Jazbinsek, M.; Gunter, P.; Wehrli, S.; Bossard, M.; Zakynthinos, P.; Tomkos, I.;
- SOFI partners contributed to a joint Special Session in collaboration with ICT FP7-NAVOLCHI on "CMOS Fabrication-Based Photonic Technologies for Communications" co-located with ICTON 2013, held in Cartagena, Spain on June 23-27, 2013

GO - Latest dissemination activities

Conferences and Symposiums

GigOptix was present at the following international exhibitions with the company booth, where we were also promoting our work within the SOFI project:

- ECOC 2012, September 16–20 2012 in Amsterdam, The Netherlands
- OFC 2013, March 19-21 2013 in Anaheim, USA

In the reporting period GigOptix contributed to the following papers:

- **'Nonlinear Nano-Photonic'**, W. Freude, L. Alloatti, M. Lauermann1 A. Melikyan, D. Korn, R. Palmer, J. Pfeifle, P. C. Schindler, C. Weimann1 R. Dinu, J. Bolten, T. Wahlbrink, M. Waldow, S. Walheim, P. M. Leufke, S. Ulrich, J. Ye, P. Vincze, H. Hahn, H. Yu, W. Bogaerts, K. Hartinger, V. Brasch, T. Herr, R. Holzwarth, C. Stamatiadis, M. F. O'Keefe, L. Stampoulidis, L. Zimmermann, R. Baets, Th. Schimmel, I. Tomkos, K. Petermann, T. Kippenberg, C. Koos, J. Leuthold; Invited paper to OSA's Annual Meeting, Frontiers in Optics 2013, October 6-10, 2013, Orlando, FL, USA.

- **'Silicon-organic hybrid (SOH) IQ modulator for 16QAM at 112 Gbit/s'**;
  Korn, D.; Palmer, R.; Yu, H.; Schindler, P. C.; Alloatti, L.; Baier, M.; Schmogrow, R.; Bogaerts, W.; Selvaraja, S.; Lepage, G.; Pantouvaki, M.; Wouters, J.; Verheyen, P.; Van Campenhout, J.; Absil, P.; Baets, R.; Dinu, R.; Koos, C.; Freude, W.; Leuthold, J.;
  Conference on Lasers and Electro-Optics Europe (CLEO-Europe/IQEC 2013), International Congress Centre Munich, Germany; Paper CK-9. 2 THU; May 12–16, 2013;

- **'Silicon-Organic Hybrid (SOH) Modulator Generating up to 84 Gbit/s BPSK and M-ASK Signals'**;
  Palmer, R.; Alloatti, L.; Korn, D.; Schindler, P.C.; Schmogrow, R.; Baier, M.; Koenig, S.; Hillerkuss, D.; Bolten, J.; Wahlbrink, T.; Waldow, M.; Dinu, R.; Freude, W.; Koos, C. and Leuthold, J.;
  Optical Fiber Communication Conference (OFC2013) Anaheim, CA; Novel Modulators (OW4J); pp. OW4J.6; March 17, 2013

- **'Silicon-organic hybrid devices'**;
  Alloatti, L.; Korn, D.; Pfeifle, J.; Palmer, R.; Koeber, S.; Baier, M.; Schmogrow, R.; Diebold, S.; Pahl, P.; Zwick, T.; Yu, H.; Bogaerts, W.; Baets, R.; Fournier, M.; Fedeli, J.; Dinu, R.; Koos, C.; Freude, W.; Leuthold, J.;
  OPTO SPIE Photonics West (OPTO-SPIE'13), San Francisco (CA), USA, paper 8629-24; Feb. 2-7, 2013,[invited]
  doi:10.117/12.2005866

- **'Silicon organic hybrid fabrication platform for integrated circuits'**
Korn, D.; Alloatti, L.; Lauermann, M.; Pfeifle, J.; Palmer, R.; Schindler, P. C.; Freude, W.; Koos, C.; Leuthold, J.; Yu, H.; Bogaerts, W.; Komorowska, K.; Baets, R.; Van Campenhout, J.; Verheyen, P.; Wouters, J.; Moelants, M.; Absil, P.; Dispenza, M.; Secchi, A.; Jazbinsek, M.; Gunter, P.; Wehrli, S.; Bossard, M.; Zakynthinos, P.; Tomkos, I.;
14th Intern. Conf. on Transparent Optical Networks (ICTON'12), University of Warwick, Coventry, UK, July 2012 **[SOFI, invited]**

Journals

In the reporting period GigOptix contributed to the following journals publications:

- **'Silicon-organic hybrid (SOH) IQ modulator using the linear electro-optic effect for transmitting 16QAM at 112 Gbit/s'**,D. Korn, R. Palmer, H. Yu, P. Schindler, L. Alloatti, M. Baier, R. Schmogrow, W. Bogaerts, S. Selvaraja, G. Lepage, M. Pantouvaki, J. Wouters, P. Verheyen, J. Van Campenhout, B. Chen, R. Baets, P. Absil, R. Dinu, C. Koos, W. Freude, and J. Leuthold, Opt. Express 21, 13219-13227 (2013).doi: 10.1364/OE.21.013219

- **'Low Power Mach-Zehnder Modulator in Silicon-Organic Hybrid Technology'**, Palmer, R.; Alloatti, L.; Korn, D.; Schindler, P.; Baier, M.; Bolten, J.; Wahlbrink, T.; Waldow, M.; Dinu, R.; Freude, W.; Koos, C.; Leuthold, J.; IEEE Photonic Technol. Lett.; Vol. 25?, Issue 99, pp. xx-yy, April 2013**,** doi: 10.1109/LPT. 2013.2260858

- **'Silicon-Organic Hybrid MZI Modulator Generating OOK, BPSK and 8-ASK Signals for up to 84 Gbit/s'**; Palmer, R.; Alloatti, L.; Korn, D.; Schindler, P. C.; Schmogrow, R.; Heni, W.; Koenig, S.; Bolten, J.; Wahlbrink, T.; Waldow, M.; Yu, H.; Bogaerts, W.; Verheyen, P.; Lepage, G.; Pantouvaki, M.; Van Campenhout, J.; Absi, P.; Dinu, R.; Freude, W.; Koos, C.; Leuthold, J.; IEEE Photonics J.; Vol. 5; Issue 2; pp. 6600907; 2013; doi: 10.1109/JPHOT.2013.2258142

IMEC - Latest dissemination activities

Conferences and Symposiums

- L. Alloati, D. Korn, J. Pfeifle, R. Palmer, S. Koeber, M. Baier, R. Schmogrow, S. Diebold, P. Dahl, T. Zwick, H. Yu, W. Bogaerts, R. Baets, M. Fournier, J.-M. Fedeli, R. Dinu, C. Koos, W. Freude, J. Leuthold, **Silicon-Organic Hybrid Devices**,(invited) publication in Proc. SPIE, United States, (to be published).
- L. Alloati, D. Korn, D. Hillerkuss, T. Valliatis, J. Li, R. Bonk, R. Palmer, T. Schellinger, A. Barklund, R. Dinu, J. Wieland, M. Fournier, J.-M. Fedeli, P. Dumon, R. Baets, C. Koos, W. Freude, J. Leuthold, **40 Gbit/s Silicon-Organic Hybrid (SOH) Phase Modulator**,accepted for publication in European Conference on Optical Communications 2010 (ECOC), Italy, (to be published).
- J. M. Brosi, C. Koos, L. C. Andreani, P. Dumon, R. Baets, J. Leuthold, W. Freude, **100 Gbit/s / 1 V Optical Modulator with Slotted Slow-Light Polymer-Infiltrated Silicon Photonic Crystal**,accepted for publication in 2008 Slow and Fast Light Topical Meeting, United States, (to be published) .
- D. Korn, H. Yu, D. Hillerkuss, L. Alloatti, C. Mattern, K. Komorowska, W. Bogaerts, R. Baets, J. Van Campenhout, P. Verheyen, J. Wouters, M. Moelants, P. Absil, C. Koos, W. Freude, J. Leuthold, **Detection or Modulation at 35 Gbit/s with a standard CMOS-processed optical waveguide**,the Conference on Lasers and Electro-Optics 2012, p.CTu1A.1 (2012) .
- Melikyan, M. Sommer, A. Muslija, M. Kohl, S. Muehlbrandt, A. Mishra, V. Calzadilla, Y. Justo, J.P. Martinez-Pastor, I. Tomkos, A. Scandurra, D. Van Thourhout, Z. Hens, M. Smit, W. Freude, C. Koos, J. Leuthold, **Chip-to-chip plasmonic interconnects and the activities of EU project NAVOLCHI**,14th International Conference on Transparant Optical Networks (ICTON 2012) (invited), United Kingdom, p.paper Th.A5.1 (2012) .
- D. Korn, L. Alloati, M. Lauermann, J. Pfeifle, R. Palmer, P.C. Schindler, W. Freude, C. Koos, J. Leuthold, H. Yu, W. Bogaerts, K. Komorowska, R. Baets, J. Van Campenhout, P. Verheyen, J. Wouters, M. Moelants, P. Absil, A. Secchi, M. Dispenza, M. Jazbinsek, P. Gunter, S. Wehrli, M. Bossard, P. Zakynthinos, I. Tomkos, **Silicon-Organic Hybrid Fabrication Platform for Integrated Circuits**,ICTON 2012 (invited), United Kingdom, p.paper Th.A5.5 (2012) .

- H. Yu, M. Pantouvaki, J. Van Campenhout, K. Komorowska, P. Dumon, P. Verheyen, G. Lepage, P. Absil, D. Korn, D. Hillerkuss, J. Leuthold, R. Baets, W. Bogaerts, **Silicon carrier-depletion-based mach-zehnder and ring modulators with different doping patterns for telecommunication and optical interconnect**,14th International Conference on Transparant Optical Networks (ICTON 2012) (invited), United Kingdom, p.paper Th.A4.3 (2012) .
- H. Yu, W. Bogaerts, K. Komorowska, R. Baets, Korn dietmar, Alloatti Luca, Hillerkuss David, Koos Christian, Freude Wolfgang, Leuthold Juerg, Van Campenhout Joris, Verheyen Peter, Wouters Johan, Moelants Myriam, Absil Philippe, **Doping Geometries for 40G Carrier-Depletion-Based Silicon Optical Modulators**,The Optical Fiber Communication Conference and Exposition (OFC) and The National Fiber Optic Engineers Conference (NFOEC) 2012, United States, p. OW4F.4 (2012) .
- W. Freude, L. Alloatti, A. Melikyan, R. Palmer, D. Korn, N. Lindenmann, T. Vallaitis, D. Hillerkuss, J. Li, A. Barkund, R. Dinu, J. Wieland, M. Fournier, J. Fedeli, S. Walheim, P.M. Leufke, S. Ulrich, J. Ye, P. Vincze, H. Hahn, H. Yu, W. Bogaerts, P. Dumon, R. Baets, B. Breiten, F. Diederich, M.T. Beels, I. Biaggio, Th. Schimmel, C. Koos, J. Leuthold, **Nonlinear optics on the silicon platform**,The Optical Fiber Communication Conference and Exposition (OFC) and The National Fiber Optic Engineers Conference (NFOEC) 2012, United States, p.paper OTh3H.6 (2012) .
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IMEC's journal publication with relation to SOFI are mainly joint publication with KIT.

- R. Palmer, L. Alloati, D. Korn, P.C. Schindler, R. Schmogrow, W. Heni, S. Koenig, J. Bolten, T. Wahlbrink, M. Waldow, H. Yu, W. Bogaerts, P. Verheyen, G. Lepage, M. Pantouvaki, J. Van Campenhout, P. Absil, R. Dinu, W. Freude, C. Koos, J. Leuthold, **Silicon-Organic Hybrid MZI Modulator Generating OOK, BPSK and 8-ASK Signals for up to 84 Gbit/s**,Photonics Journal, 5(2), p.6600907 (2013) .
- H. Yu, D. Korn, M. Pautouvaki, J. Van Campenhout, K. Komorowska, P. Verheyen, G. Lepage, P. Absil, D. Hillerkuss, J. Leuthold, R. Baets, W. Bogaerts, **Using carrier-depletion silicon modulators for optical power monitoring** ,Optics letters, (2012) .
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- D. Korn, R. Palmer, H. Yu, P.C. Schindler, L. Alloati, M. Baier, R. Schmorow, W. Bogaerts, S. Selvaraja, G. Lepage, M. Pantouvaki, J.M.D. Wouters, P. Verheyen, J. Van Campenhout, B. Chen, R. Baets, P. Absil, R. Dinu, C. Koos, W. Freude, J. Leuthold, **112 Gbit/s silicon-organic hybrid (SOH) IQ modulator using the linear electro-optic effect**,submitted for publication in Optics Express, (submitted).

Other Dissemination Activities

IMEC Organized a workshop on *Hybrid Silicon Photonics* at the European Conference on Optical Communication (ECOC) in Amsterdam, September 2012. The half-day workshop was attended by over 50 people and had several high-profile international speakers

- John Bowers, UCSB
- Juerg Leuthold, KIT,
- Lionel Kimerling, MIT
- John Kouvetakis, ASU
- Nicolas Izard, UP-Sud
- Peter Verheyen, IMEC

The focus of the workshop was on the integration of novel photonic materials in the CMOS-like environment of silicon photonics, and the benefits that this integration can bring. The SOFI project was organizer of this project, and the results of the project were prominently present in the presentation by Prof. Leuthold.

KIT - Latest dissemination activities

Conferences and Symposiums

'Silicon-Organic Hybrid (SOH) Frequency Comb Source for Data Transmission at 784 Gbit/s'
C. Weimann et al.; ***ECOC 2013***

'High-Speed Silicon-Organic Hybrid (SOH) Modulator with 1.6 fJ/bit and 180 pm/V In-Device Nonlinearity'
Palmer et al.; *ECOC 2013*

'Silicon-organic hybrid (SOH) IQ modulator for 16QAM at 112 Gbit/s';
Korn, D.; Palmer, R.; Yu, H.; Schindler, P. C.; Alloatti, L.; Baier, M.; Schmogrow, R.; Bogaerts, W.; Selvaraja, S.; Lepage, G.; Pantouvaki, M.; Wouters, J.; Verheyen, P.; Van Campenhout, J.; Absil, P.; Baets, R.; Dinu, R.; Koos, C.; Freude, W.; Leuthold, J.;
Conference on Lasers and Electro-Optics Europe (CLEO-Europe/IQEC 2013), International Congress Centre Munich, Germany; Paper CK-9. 2 THU; May 12–16, 2013;

‘Surface Plasmon Polariton High-Speed Modulator’
A. Melikyan et al; **Postdeadline Paper** CLEO 2013

'First monolithic GaAs IQ electro-optic modulator, demonstrated at 150 Gbit/s with 64-QAM,';
Korn, D.; Schindler, P. C.; Stamatiadis, C.; O’Keefe, M. F.; Stampoulidis, L.; Schmogrow, R.; Zakynthinos, P.; Palmer, R.; Cameron, N.; Zhou, Y.; Walker, R. G.;Kehayas, E.; Tomkos, I.; Zimmermann, L.; Petermann, K.; Freude, W.; Koos, C.; Leuthold, J.;
Optical Fiber Communication Conference (OFC'13), Los Angeles, Anaheim (CA), USA, 17.–21.03.2013
Postdeadline Paper PDP5C.4

'Silicon-Organic Hybrid (SOH) Modulator Generating up to 84 Gbit/s BPSK and M-ASK Signals';
Palmer, R.; Alloatti, L.; Korn, D.; Schindler, P.C.; Schmogrow, R.; Baier, M.; Koenig, S.; Hillerkuss, D.; Bolten, J.; Wahlbrink, T.; Waldow, M.; Dinu, R.; Freude, W.; Koos, C. and Leuthold, J.;
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'Silicon-Organic Hybrid - a path towards active silicon photonic devices' ;
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14th Intern. Conf. on Transparent Optical Networks (ICTON'12), University of Warwick, Coventry, UK, July 2012
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Journals

‘Silicon-Organic Hybrid Electro-Optical Devices’
Leuthold et al., *JSTQE 2013*

‘High-Speed Plasmonic Phase Modulator’
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‘Silicon-organic hybrid (SOH) IQ modulator using the linear electro-optic effect for transmitting 16QAM at 112 Gbit/s’

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