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Photonic Electronic Integration

Key Technologies for Communication and Sensor

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Summary

Performant and efficient information processing, distribution and storage is essential for the digitisation of the economy and society. Microelectronics are developing at a rapid pace and require photonics in processing technology, data communication and sensor technology as a necessary supplement. Rapidly increasing data rates and new applications like THz radio, coherence tomography, machine vision, LIDAR and quantum information processing increasingly require the use of photonic technologies. Both technologies can only fully realise their effect if electronics and photonics are intelligently integrated.

Integrated photonic transceivers offer an enormous potential for improvement in comparison to electronic transceivers with respect to the achievable data rate, range, energy efficiency and compactness. Integrated optical sensors allow for spatial vision with improved resolution and lower costs than conventional solutions. Combined with application-specific electronic circuits, they pave the way for new System-on-Chip (SoC) and System-in-Package (SiP) solutions with unprecedented integration density. The market for silicon-photonics components alone is estimated at USD 3.5 billion [1], and the entire optical transceiver market was more than USD 6 billion in 2019 [2]. Both figures demonstrate the high market potential of photonic-electronic integrated products.

Throughout the world, initiatives like Petra [3] in Japan, DARPA's Electronics Re-urgence Initiative with projects like PIPES[4] and LUMOSA and industrial consortia like COBO [5] and CPO [6] are concentrating on driving photonic-electronic integration forward. In Germany, the DFG is promoting basic research in this field as part of a focused programme [7]. However, a variety of challenges have to be solved for commercial implementation. The federal government's high-tech strategy emphasises the fundamental importance of microelectronics for Germany. In conjunction with the photonics segment, with which German industry achieved a turnover of EUR 3 billion in 2018 [8], the opportunities offered by photo-electronic integration in future-oriented fields like communications, Industry 4.0 and mobility must be taken advantage of now. To this end, 1) a promotional initiative for photonic-electronic integrated circuits, 2) the further development of silicon as an integration platform, including heterointegration and 3) the drafting of an industrial strategy for photonic-electronic microchips are recommended.

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Introduction

Highly innovative technologies like microelectronics and nanoelectronics and, increasingly, photonics, are playing a more and more central role in our lives. They not only penetrate everyday information and communication technology; they also increasingly connect our society. They pave the way to a new information society and continuously further it in rapid development cycles. Digitisation makes information technology an essential component of our lives. Information is almost exclusively transported on a global optical network. It is accessed wirelessly using mobile end devices. In the future, production plants and machines will also be integrated into the communication network as will many devices that surround us in our daily lives which will result in completely new services and functions, as well as challenges, that will permanently impact our society. To continue to meet the requirements of the continuously increasing quantity of information, the energy requirements and costs per transmitted bit has to be drastically decreased again. The current quantity of data transmitted per resident in Europe is approximately 43 GB/month and should increase to approximately 117 GB/month per resident in 2022 [9]. It is expected that in 2022, in addition to 4.8 billion people (approximately 60% of the global population), around 28.5 billion devices will use the Internet. More than half of those will communicate exclusively with other devices (Internet of Things: IoT). Internet video streaming will triple by 2022 and online gaming remains a trend that is projected to increase tenfold with respect to data volume. The growth rate of all Internet traffic is estimated at 25%-80% per year, depending on the network segment, type of traffic (IP, video, mobile data, IoT) and the geographic region [10]. The share of global power consumption by communication systems will then be approximately 8%. To realise this increase in transmitted data volume while simultaneously decreasing energy consumption, integration in the information processing systems that far exceeds the current status is required.

The mastery of electronics was, and is, crucial for the innovative power in Germany. Electronics in general and the ability to develop and manufacture electronic systems are essential for the success of research and industry. Due to its innovative power and system expertise, in conjunction with far-reaching technology and component competence, Germany holds a top position in the research and industrial landscape.

In the past 50 years, according to Moore's Law, a doubling of the number of transistors per area has been achieved in the electronics segment approximately every 18 months which allowed for very high computing capacities to be implemented on an integrated circuit. Electronic chip-to-chip communication is increasingly becoming a bottleneck because the bandwidth of the electrical lines is limited. The energy the electrical data interfaces consume is also reaching a critical size. In addition, electronic packaging can barely further increase the number of IO pins. Currently, a bandwidth or data rate of at maximum 25 Gbit/s or 50 Gbit/s per I/O pin can be achieved. 100 Gbit/s are already in development, but also have limits that can only be overcome by optical solutions. High-capacity processors have memory bandwidths of more than 10 Tbit/s and switches for routers will even exceed 50 Tbit/s in the near future, a fact which already requires several hundred high-speed I/O pads [11]. For further scaling, optical I/O interfaces and optical transceivers are crucial components to further increase the data transfer speeds of electronic multi-chip modules and the systems set up with them. Disruptive solutions are therefore necessary to close this gap, and photonic integration offers this potential. Thus, for instance, the direct coupling of fibre-chips in silicon-photonic technology provides bandwidths of more than 12 THz (100 nm/edge-coupling) and 5 THz (40 nm/ grating coupler) per optical I/O pad [12]. The scaling of photonic circuits at 30% per year does not, however, follow Moore's Law entirely. Therefore, the gap between the continuously increasing demand for bandwidth or transmission rates and the increase in the performance capacity of the transceiver must be closed.

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Photonic-Electronic Integration

Many photonic components can already be integrat- ed into a silicon-based CMOS-compatible process. A thin layer of silicon (a few tenths of a micrometre) on silicon-oxide acts as a wave conductor and to realise purely optical components like filters. Modulators based on doped wave conductor structures or electro-optical polymers can also be realised on silicon. The integration of germanium layers allows for the realisation of high- ly efficient photodetectors. Complex modulators and detector systems can also be integrated into this Sili- con-on-Insulator" (SOI) technology; currently, however, the light source still has to be applied as a hybrid. This requires innovative, scalable assembly and connection technologies like wafer bonding or transfer printing. New research approaches are dedicated to the (monolithic) hetero-integration of components based on compound semiconductors (e.g., electro-optical converters or ul- tra-fast transistors) with the high-performance silicon technology (CMOS or bipolar transistors). Europe and Germany are even global leaders in the field of ul- tra-broadband SiGe BiCMOS high-speed technologies. Thus, photonic-electronic integration already plays a major role in realising optical transceivers. The further increase in the demand for transmission capacities re- quires further efforts in research and development in a short period of time.

The integration procedure is multidimensional. One di- mension is the parallelisation of components and func- tions on which work is already being done. The second dimension, photonic-electronic integration, opens up degrees of freedom in the design of systems that are still largely unused. This blurs the lines between purely optical and purely electronic signal processing. Other dimensions include, e.g., costs, power dissipation and the data rate per function block. A holistic approach is required for photonic-electronic integration, that allows for synthesis and analysis technologies and the simulation in all degrees of freedom of light (time, frequency, space and polarisation). In a focussed programme from the Deutsche Forschungsgemeinschaft (German Re- search Association), the bases for integrated photonic communication systems with the highest bandwidths is being examined. For instance, what was only possible 10 years ago using purely optical signal processing can now be realised using high-performance digital elec- tronics and appropriate software. The most important progress is expected from the combination of optical and electronic signal processing, which is also utilised outside telecommunications, e.g., for LIDAR, optical coherence tomography (OCT), multi-modal endoscopy and microscopy as well as in the future-oriented field of quantum photonics with applications in sensor technology and communications. Innovative methods, viewed on the system level, must not result in an increase in energy consumption. Energy efficiency and sustainability are an important premise in researching this new field which is aimed at merging microelectronics and photonics.

Fields of Research

A) Transceiver chiplets for electronic Systems-in-Package with the highest capacities

A drastic increase in the I/O bandwidth while keeping the space and energy requirements the same as required for the next generation of switch ASICs with more than 10 Tbit/s of throughput per chip, requires a massive modularisation and parallelisation in one or several dimensions. Thus, electronic modules should be integrated with photonic modules that allow for a data rate of 100 Tbit/s per overall module. The energy consumption should be less than a picojoule per bit. To optimise the throughput, the number of modulation levels can be increased in addition to the space, time, frequency and polarisation multiplex. This should allow for the realisation of data connections with unprecedented use of bandwidth, the highest level of efficiency and maximum range. The consequence is a general introduction of embedded photonic chips for signal transmission in advanced microelectronic systems. In addition to FPGAs and special ASICs, photonic connectivity for central units (CPUs), graphics processors (GPUs) and domain-specific accelerators have an impact on a variety of applications with a wide range of uses, including artificial intelligence, machine-based learning and large-scale emulation and high-performance computing (HPC) applications.

B) Terminal technology for next-generation optical networks

In the next generation of optical networks, the enormous bandwidth of the fibre optics of approximately 70 THz is better exhausted in a first step by using several transmission bands. Another increase in the transmission capacity can be achieved by using the spatial dimension either in a fibre or with multiple fibres. If they come from different directions (2 to 6), multiple coherent transceivers are required in these nodes. The state-of-the-art are nodes in which one or two optical carriers are processed by a transceiver. The ASIC (Application Specific Integration Circuit) therein includes digital signal processing (DSP) and a photonic module. Processing dozens of such channels requires highly integrated solutions. Here, the issue is a suitable architecture and suitable components which, in addition to offering high performance, must also have a high degree of parallelism. Optical signal sources like optical frequency combs used by several channels or the use of individual optical functions by several carriers are of fundamental importance here. This is accompanied by an increase in the symbol rate to more than 100 GBd per optical carrier. Higher modulation formats require a very good signal-to-noise ratio of all components in the signal path and a higher resolution of the converters in the transceivers at the highest scan rates (>120 Gs/s). This places extremely high demands on semiconductor technologies and circuit design. Optical technologies for analogue-digital and digital-analogue conversion (ADC & DAC) are interesting here. Classical assembly technologies are reaching their limits here. The connections between optics and electronics must be realised with practically no losses which is difficult with separate housings. The plurality of channels and the high data rates also place extremely high demands on the synchronisation of the components in such complex nodes which can be fulfilled with innovative optoelectronic oscillators. With hybrid integration, the benefits of very low clock fluctuation (low-jitter, low skew) in signal routing and transmission can be utilised which allows for a further increase in integration density. This massive increase in complexity and data throughput must be enabled with a sublinear increase in the power consumption and space requirement.

Detectors and modulators based on classical semiconductor technologies are currently reaching the limits of their possibilities in the current transmission systems with respect to maximum signal bandwidth. The first promising results demonstrate, however, that new material systems (e.g., based on graphene) can offer a way out thanks to the extremely high intrinsic mobility of the carriers. A central task is to integrate these material systems into photonic integrated circuits (PICs) on a scalable, e.g., SOI or silicon-nitride-based technology platform.

C) New solutions for optical sensor technology, microwave photonics and THz technology

The low attenuation of the glass fibres allows for monitoring of the infrastructure of systems and devices or for point-of-care diagnostics in medical engineering by embedded optical sensors. LIDAR-on-a-Chip or 3D imaging for optical coherence tomography (OCT) offer cost-efficient solutions in imaging procedures with significantly improved performance, e.g. an increase in the local resolution or an increase in the image rate. Photon- ic-electric integrated LIDAR systems will play an import- ant role in future applications like autonomous driving. Different wavelength ranges like those for visible and infra-red light or mm-wave emission can be combined. The use of multiple sensors or wavelength ranges requires a highly precise synchronisation using low-noise master oscillators and a precise distribution of the clock signals. In addition to improved resolution and increased range, specifications include a reduction in the observation time and the costs.

Microwave photonics will play a significant role in fifth and sixth mobile communication networks (5G, 6G) and radar sensor systems. In addition to the generation and transport of radio waves, optical signal processing will also be essential in multi-beam antenna technologies in the future. The realisation of a seamless transition from the actual wireless signal transmission to the photon- ics is important here. In multi-antennas radar systems, the angular resolution depends directly on the antenna aperture. By using microwave photonics, significantly larger apertures can be realised which allow for, e.g., the autonomous operation of significantly improved ra- dar imaging. Optical oscillators have significantly lower phase noise than electronic oscillators and allow for the generation, distribution and processing of signals of the highest quality in communication and measuring devices. With hybrid integration, the benefits of higher tempo- ral precision in signal routing and transmission can be exploited to allow for a further increase of the integration density, e.g., in phased array antenna technologies.

Photonic-electronic integrated systems are also highly important for applications in THz technology (e.g., sensors with THz signals). Thus, THz signal sources, for instance, can be easily realised by photo-mixing two optical laser sources. The integration of plasmonic converters with THz antennas in a very small space may lead to the detection and emission of radio waves in the THz range and the direct conversion thereof into or from the optical domains. This would allow for a transparent transmission of signals from the fibre into THz radio waves and thus, e.g., the cost-efficient, wireless connection of end devices and users with data rates of up to 100 Gbit/s and more. Other applications include 3D sensing for face recognition with mobile telephones and in vehicles.

D) Analogue optical signal processors

Today, electronic systems are usually used to process signals and perform non-linear operations. While optical carriers are used to transmit immense data quantities up to several 1000 km, the basic functions required in an optical network, like switching/routing, wavelength and format conversion, phase conjugation, phase-sensitive amplification, optical Fourier transformn and regeneration of the signals in amplitude and phase can be realised with integrated optical platforms. By integrating several components on a technological platform, a considerable level of complexity has already been reached. Each of these technologies has their specific challenges which have to be solved soon in order to develop complex functional optical signal processing solutions. Analogue optical signal processing is the basis for systems used for quantum information processing. Linear and power-efficient signal processors built by co-integrating electronics and photonics can support applications in artificial intelligence. Furthermore, photonic processors could assume the direct signal processing in systems for THz mobile communication in the future. An interest- ing development trend includes programmable optical circuits which consist of several of the same unit cells and can be reprogrammed to realise a variety of functions with the help of a corresponding electrical control system.

E) Further development of silicon as an integration platform

A challenge with respect to photonic-electronic integration lies in the various material systems used. Silicon is the most important semiconductor material in electronics and will also be the basis of electronic circuits to further scale down to smaller structure sizes. The wavelength lengths of around 1.5 µm (minimal attenuation) or 1.3 µm (minimal chromatic dispersion) have established themselves for the optical transmission to the glass fi- bres. These wavelengths demand III/V semiconductor materials to generate light. Experiments on integrating such light sources monolithically on silicon are being performed, but they are still in the early research stages and it will be several years before they will be industri- ally applicable. Without abandoning the long-term goal of monolithic integration of active optical components and electrical circuits, hybrid integration technologies are being examined in the meantime. Today, photonic components are manufactured on several platforms like Si, InP, SiO, LiNbO3, SiN, polymers and glass. Depending on the application, they have their specific advantages and disadvantages. That is why several material systems are currently used in products like optical transceivers. InP-based optical sources or amplifiers are connected in a hybrid manner to modulators and wave guide components, e.g., on silicon on an insulator basis. In particular, each optical coupling point is critical for the functionality and efficiency of the optical circuit and requires precise and reliable solutions. These challeng- es are being addressed by combining different material systems on one chip using hybrid integration approach- es. Thus, plasmonic structures, for instance, can be used with non-linear polymers or materials like BaTiO or Lithium Niobate-on-Insulator (LNOI) to create mod- ulators with extremely high bandwidth (>100 GHz). The integration of such structures into photonic-electronic integrated circuits is an important matter. The thermal behaviour of complex photonic-electronic integrated cir- cuits also brings up interesting questions. The benefit of silicon in electronics is operation at high junction and environmental temperatures. When using hetero-integration of compound semiconductors, active cooling often has to be used, a fact which makes construction and housing concepts significantly more difficult and increases power consumption. Approaches that allow for stable operation at high temperatures are therefore very interesting here. Another practical topic is avoiding reflections, in particular at the interface to lasers or gain elements. Integrable isolators with usable specifications still do not exist despite several years of research. Mi- cro-optic isolators usually require a hermetic and, thus, expensive housing or they cannot be directly integrated. With respect to reflection sensitivity, quantum dot lasers may offer a way out.

One important open topic is the development of gener- ally cost-efficient packaging concepts which do not re- quire hermeticity when integrating III/V and other semi- conductor components and which can be manufactured and assembled fully automatically to the greatest pos- sible extent. For reasons of simplicity, the packaging concepts in microelectronics (LGA/BGA packages) will be used as a basis and are also highly relevant in topic A). When realising complex optical transceivers, it would be beneficial to standardise transceiver chiplets or sub-functions thereof with respect to dimensions and functions, thus making them interchangeable/pluggable in order to achieve adequately high exploitation in large silicon photonic multi-chip modules.

The requirements with respect to realising low-loss and cost-efficient fibre-coupling technology for photon- ic-electronic integrated circuits are high. Comprehensive studies on taper structures and, e.g., grating-supported coupling structures are already under way. However, the coupling is still achieved with active adjustment because precision is required in the sub-micrometre range; here, in terms of cost-efficiency, a transition to passively cou- pled structures is required. Not only must the coupling structure be examined, but also the fibre connection as such. Pluggable fibre connections could, for instance, be a promising alternative to adhesive fibre arrays. How- ever, they pose mechanical (size, stability, adjustment precision) and thermal challenges with respect to processing. Joint developments in the core technologies in the field of photonics are the key to successfully devel- oping the markets via industry.

Recommended Actions

The major technological challenges in the field of photon- ics and microelectronics with respect to photonic-elec- tronic integration cannot be overcome by one company or one research institute alone. However, the conditions in Germany are excellent to face the challenges together and utilise the opportunities photonic-electronic integration offers in future-oriented fields like communication, Industry 4.0 and mobility.

The photonics industry in Germany comprises approx- imately 1,000 companies with more than 135,000 em- ployees. Around 50 companies, 20 universities and research institutes are working on optical communi- cations technology in Germany. Five of the ten largest optical network suppliers have research and develop- ment sites in Germany. With the Leibniz Institute for In- novative Microelectronics IHP, the Ferdinand Braun In- stitute FBH and the Fraunhofer Heinrich-Hertz Institute HHI and the Fraunhofer Institute IAF, extra-university re- search institutes are available for prototype production of InP, silicon-photonics and high-speed electronics on a silicon-germanium basis. Photonic-electronic integra- tion also offers the ability to utilise the Forschungsfab- rik Mikroelektronik Deutschland (FMD) as a whole and open it up for commercial use.

Specifically, the following measures are recommended:

1. Initiating a promotion programme to research promising photonic-electronic integrated solutions for communications and sensor technology in industry-guided joint projects and develop them until they are ready for application. This also includes expanding prototyping and small series production capacities to accelerate the market introduction of research findings in the user industry. The use of global production partners must also be possible if there are no suitable partners in Germany.

2. Further developing technologies for the hetero-integration of silicon photonics, silicon electronics, III-V compound semiconductors and innovative materials and for optical chip coupling. Special attention must be paid to robust and resilient procedures that allow for a high level of exploitation and automatic assembly technology. Collaboration with leading commercial semiconductor manufacturers is critically necessary but hasnbecome more and more difficult recently for cost/benefit reasons. Therefore, new collaboration models must be developed which enable, in particular, small to medium-sized companies and research institutes to conduct their innovative developments on the basis of current leading-edge technologies.

3. The formulation of an industrial strategy coordinated at least in Germany, but preferably also in the European Union, for the largely automated production of photonic-electronic integrated microchips is indispensable. Today, semiconductor factories for such products exist almost exclusively in Asia and the USA. To reinforce technological sovereignty, local semiconductor manufacturers must be strengthened for high-volume production in Germany or Europe with the objective of catching up or re-industrialising and bringing back production and testing in the field of photonics and electronics. Prerequisites include state-of-the-art qualified processes, comprehensive design and testing support, standardising functional blocks with respect to their physical and functional parameters as well as competitive commercial framework conditions. The latter can be established by a combination of various measures. Suitable measures include better fiscal promotion of R&D, a reasonable reduction of the high power and water costs incurred as a result of production, ensuring the planning certainty of future production costs and promoting the establishment of production facilities.

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