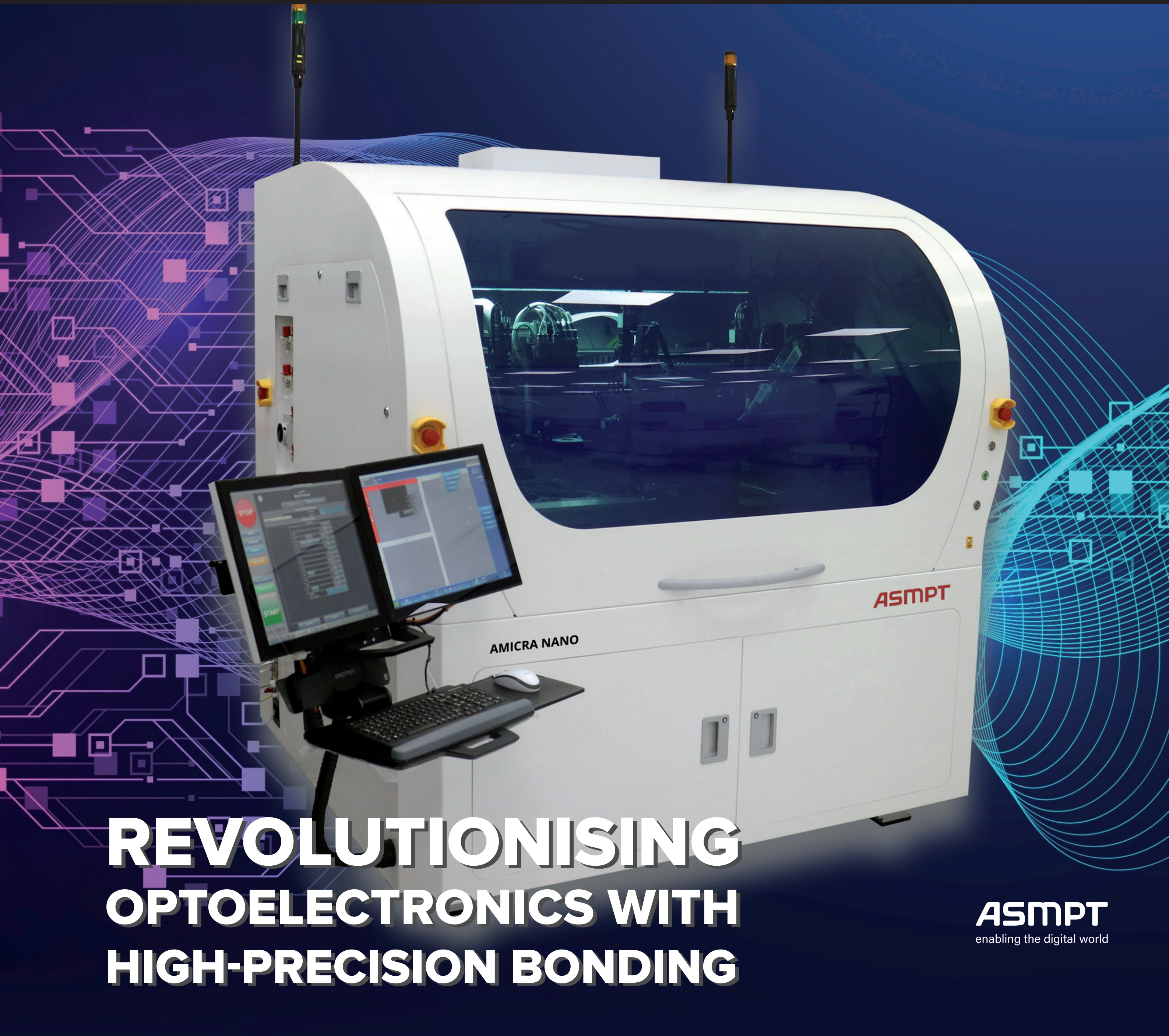
PHOTONIC INTEGRATED CIRCUITS

CONNECTING THE PHOTONIC INTEGRATED CIRCUITS COMMUNITY



REVOLUTIONISING OPTOELECTRONICS WITH HIGH-PRECISION BONDING

ASMPT
enabling the digital world

ISSUE III 2024

AN ANGEL BUSINESS COMMUNICATIONS PUBLICATION

PICMAGAZINE.NET

INSIDE
News Review, Features
News Analysis, Profiles
Research Review
and much more...

Integrated photonic platforms: The case for SiC

The potential of SiC integrated photonics is starting to be unleashed, thanks to the unique photonic properties of this material

Silicon-organic hybrid slot waveguide modulators

Scalable silicon photonics with organic materials offers a path towards optical transceivers with unprecedented performance and efficiency

Integrating high-speed germanium modulators

A major bottleneck in optical transmission is emerging, as silicon Mach-Zehnder modulators approach their limits

E V G®
invent
innovate
implement
www.EVGroup.com
INDUSTRY LEADING WAFER PROCESSING EQUIPMENT FOR PHOTONIC INTEGRATED CIRCUITS
Optical and Nanoimprint Lithography
Temporary and Permanent Wafer Bonding
NILPhotonics® Competence Center
EVG®7300
Multifunctional UV Nanoimprint Lithography System
GET IN TOUCH to discuss your process development and manufacturing needs
www.EVGroup.com

VIEWPOINT

By Laura Hiscott, Editor

A new era for optical networking?

In industry, as in all aspects of life, actions speak louder than words. So, while it's clear that photonics is on an upwards trajectory (driven largely, of course, by AI), a powerful affirmation came from this summer's announcement of Nokia's deal to acquire Infinera for $2.3 billion.

Infinera, which was established in 2001, has been a trailblazer of large-scale indium phosphide PIC manufacturing, but it isn't necessarily well known outside the photonics ecosystem. When a household name such as Nokia, whose brick mobile phones many of us carried around decades ago, buys the company, that looks like a major vote of confidence. Indeed, Infinera's stock jumped almost 20 percent in the wake of the news.

The rationale for the merger is manifold. First, the deal boosts Nokia's strength in optical networking by 75 percent, which it describes as being one of three 'pillars' in its networking infrastructure business, alongside fixed networks and IP networks. Moreover, the companies, which highlighted their shared commitment to innovation, hope that pooling their resources will accelerate their product roadmaps, while also making for a more vertically integrated company, with greater in-house capabilities.

Besides the sheer increase in scale, Nokia also mentioned the complementarity of the businesses, in terms of customers and geography. Over 30 percent of Infinera's client base are internet content providers, referred to by Nokia as 'webscale' customers, helping Nokia to hasten its expansion in this segment, which it noted is the fastest growing in the market. Infinera's presence in North America also complements Nokia's existing strengths across the rest of the world.

Based on the expectation of the transaction completing in the first half of 2025, Nokia's ambition is to achieve over 10 percent earnings per share accretion, and €200 million in operating profit synergies, in 2027.

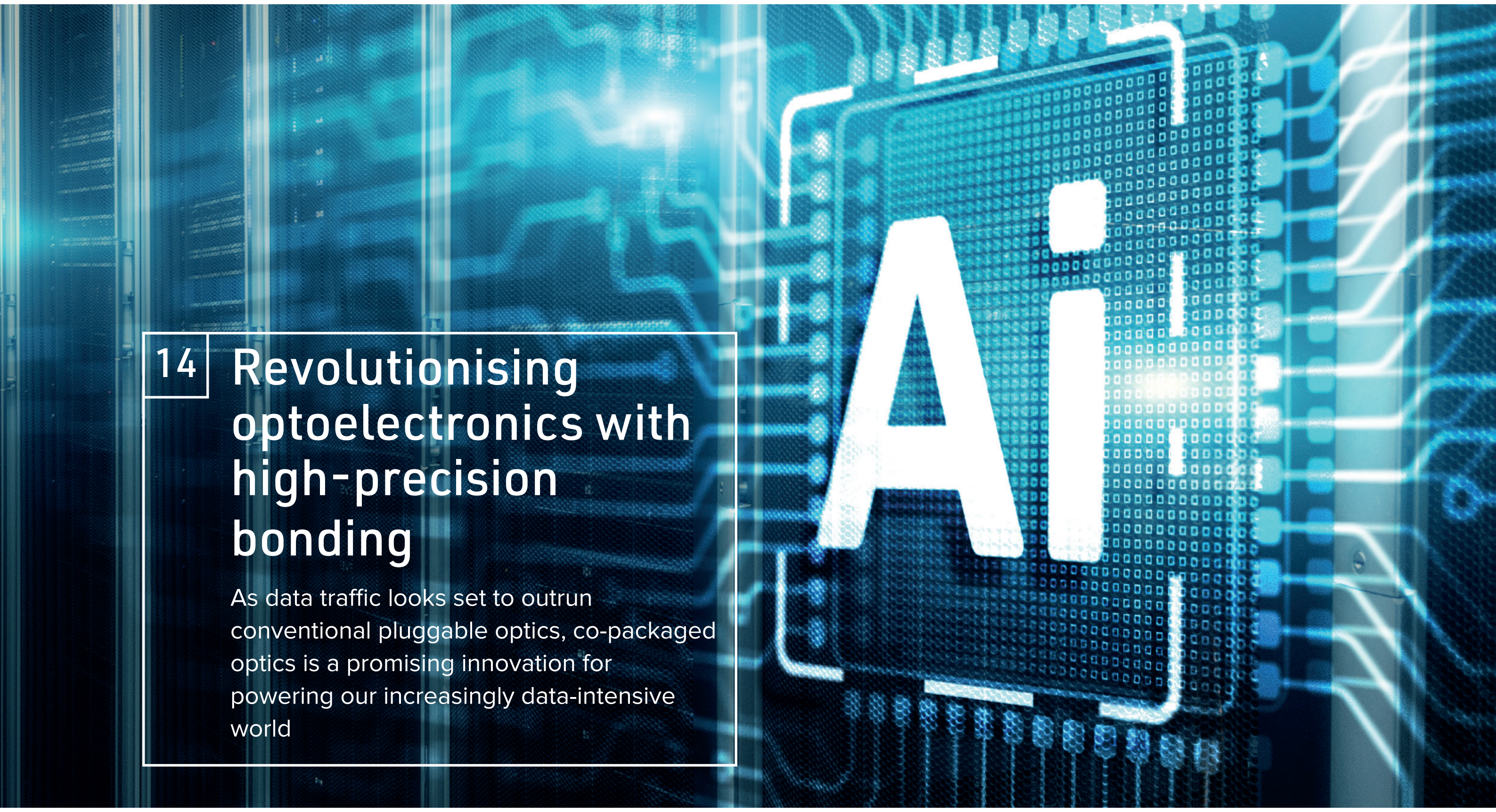
The company pointed to similarities between the businesses, as well as some of its previous acquisitions, as evidence that it can manage the merger smoothly and optimise the results.

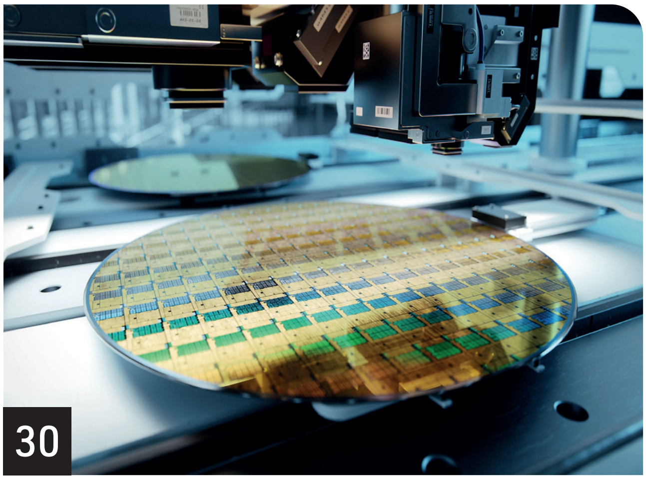
But besides the direct impacts on the two companies themselves, this deal will also change the landscape of the industry more broadly. Nokia acknowledged that there remains a long tail of small players in optical networking equipment, and that the companies hope their combined size will give them a competitive edge. If something is a good idea, more than one person will probably have thought of it.

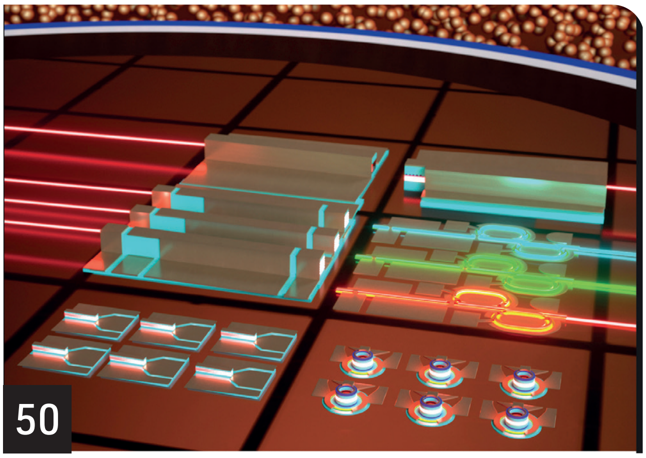
Might there be more announcements on the horizon, with more smaller providers coalescing into fewer larger ones? Only time will tell, but perhaps we are witnessing the industry maturing into a new era.

CONTENTS

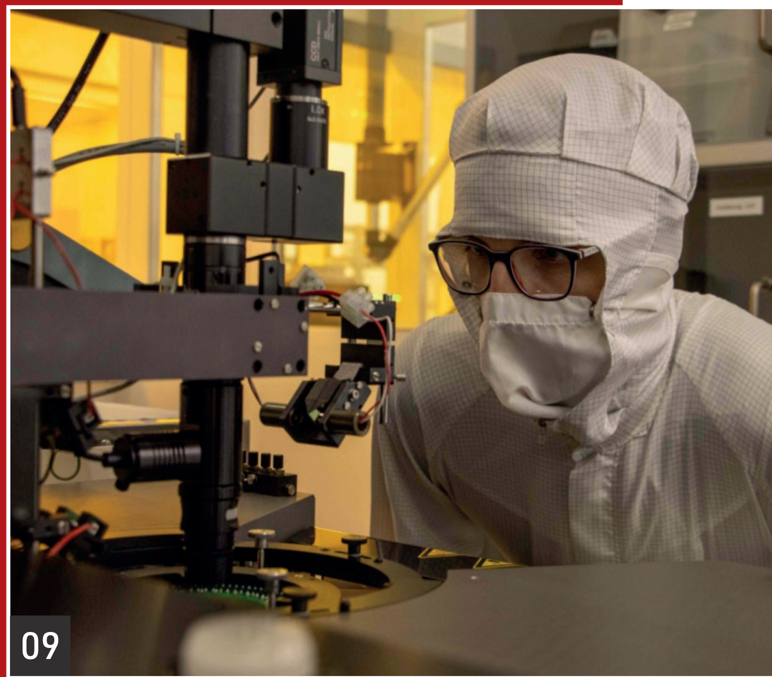
VOL. 28 ISSUE III 2024







NEWS



PHOTONIC INTEGRATED CIRCUITS

Editor
Laura Hiscott laura.hiscott@angelbc.com
Contributing Technical Editor
Richard Stevenson richard.stevenson@angelbc.com +44 (0)1923 690215
Sales & Marketing Manager
Shehzad Munshi shehzad.munshi@angelbc.com +44 (0)1923 690215
Design & Production Manager
Mitch Gaynor mitch.gaynor@angelbc.com +44 (0)1923 690214
Publisher
Jackie Cannon jackie.cannon@angelbc.com +44 (0)1923 690205

CEO Sukhi Bhadal sukhi.bhadal@angelbc.com +44 (0)2476 718970
CTO Scott Adams scott.adams@angelbc.com +44 (0)2476 718970

Published by
Angel Business Communications Ltd
6 Bow Court, Fletchworth Gate,
Burnsall Road, Coventry CV5 6SP, UK.
T: +44 (0)2476 718 970
E: info@angelbc.com

Angel BUSINESS COMMUNICATIONS

Atom interferometry performed with silicon photonics

Researchers report the first demonstration of the quantum sensing technique, representing a milestone in the development of miniaturised GPS-independent quantum navigation devices

RESEARCHERS from Sandia National Laboratories have reportedly for the first time used silicon photonic microchip components to perform a quantum sensing technique called atom interferometry, an ultra-precise way of measuring acceleration.

The scientists say this is the latest milestone towards developing a kind of quantum compass for navigation when GPS signals are unavailable. The team's findings, and their introduction of a new high-performance silicon photonic modulator, have been published as the cover story in the journal *Science Advances*.

"Accurate navigation becomes a challenge in real-world scenarios when GPS signals are unavailable," said Sandia scientist Jongmin Lee.

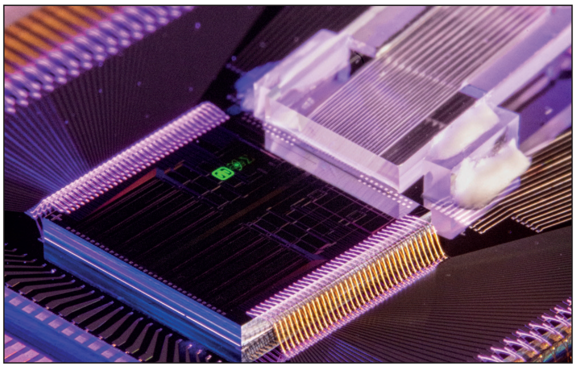
In a war zone, these challenges pose national security risks, as electronic warfare units can jam or spoof satellite signals to disrupt troop movements and operations. But quantum sensing offers a solution.

"By harnessing the principles of quantum mechanics, these advanced sensors provide unparalleled accuracy in measuring acceleration and angular velocity, enabling precise navigation even in GPS-denied areas," Lee said.

A modulator at the centre of a chip-scale laser system

Typically, an atom interferometer is a sensor system that fills a small room. A complete quantum compass — more precisely called a quantum inertial measurement unit — would require six atom interferometers.

But Lee and his team have been looking for ways to reduce its size, weight, and power needs. The scientists say they have already replaced a large, power-hungry vacuum pump with an avocado-sized vacuum chamber and consolidated several components usually delicately arranged across an optical table into a single, rigid apparatus.



The new modulator is the centrepiece of a laser system on a microchip. Rugged enough to handle heavy vibrations, it would replace a conventional laser system typically the size of a refrigerator.

Lasers perform several jobs in an atom interferometer, and the Sandia team uses four modulators to shift the frequency of a single laser to perform different functions. However, modulators often create unwanted echoes called sidebands that need to be mitigated.

According to the researchers, Sandia's suppressed-carrier, single-sideband modulator reduces these sidebands by an unprecedented 47.8 decibels — a measure often used to describe sound intensity but also applicable to light intensity — resulting in a nearly 100,000-fold drop.

"We have drastically improved the performance compared to what's out there," said Sandia scientist Ashok Kodigala.

More affordable and mass-producible silicon devices

Besides size, cost has been a major obstacle to deploying quantum navigation devices. Every atom interferometer needs a laser system, and laser systems need modulators. "Just one full-size single-sideband modulator, a commercially available one, is more than $10,000," Lee said.

Miniaturising bulky, expensive components into silicon photonic chips helps drive down these costs. "We can make hundreds of modulators on a single 8-inch wafer and even more on a 12-inch wafer," Kodigala said.

And since they can be manufactured using the same process as virtually all computer chips, "This sophisticated four-channel component, including additional custom features, can be mass-produced at a much lower cost compared to today's commercial alternatives, enabling the production of quantum inertial measurement units at a reduced cost," Lee said.

As the technology gets closer to field deployment, the team is exploring other uses beyond navigation. Researchers are investigating whether it could help locate underground cavities and resources by detecting the tiny changes these make to Earth's gravitational force. They also see potential for the optical components they invented, including the modulator, in LiDAR, quantum computing, and optical communications. "I think it's really exciting," Kodigala said. "We're making a lot of progress in miniaturisation for a lot of different applications."

Sivers plans photonics spin-off

Merger expected to unlock value and create an independent US NASDAQ traded photonics company

SIVERS SEMICONDUCTORS AB has entered into a non-binding letter of intent to merge its Sivers Photonics Ltd subsidiary with byNordic Acquisition Corporation, a publicly-traded special purpose acquisition company.

The merger is expected to unlock significant value and create an independent US NASDAQ traded photonics company. (Sivers Photonics currently has approximately 80 percent of its net revenue in the US).

Once the merger is finalised, the company plans to establish headquarters in Silicon Valley, CA with the manufacturing operations remaining in the UK.

Sivers today consists of two subsidiaries addressing two different markets: Wireless and Photonics.

The Sivers' Photonics subsidiary has particular focus on InP technology, with which it develops customisable lasers aimed at high-growth AI infrastructure and sensing applications for data centres, consumer healthcare and automotive LIDAR. The company has three issued patents and 16 patents pending across the US, UK, Canada and the World Intellectual Property Organisation.

Additionally, Sivers Photonics has development contracts to develop unique lasers for several leading silicon photonics providers, such as Ayar Labs, and is in discussion with several leading AI companies, including hyperscalers.

Subsequent to the proposed spin-off and Sivers Photonics merger combination, Sivers' remaining wireless business will consist of a portfolio of products in mmWave beamformer front-end integrated circuits, RF transceivers, repeaters, and software algorithms for mmWave RF performance for satellite and 5G Infrastructure.

Wireless business net revenue growth was 155 percent in 2023, reaching approximately $15 million. These markets are developing rapidly, and Sivers has secured a number of contracts and design wins that are projected to drive significant product revenue growth over the next 3-5 years.

"We believe the potential for AI Photonics is immense yet overshadowed by the equally exciting Sivers´ Wireless business unit. With the attractive opportunity for silicon photonics in AI infrastructure and the emerging demand for photonic biometric sensors, we feel now is the right time to shine a light on this business unit as a standalone entity to gain access to the US capital markets and create an opportunity for our shareholders to participate in its potential future success," said Bami Bastani, Sivers Semiconductor chairman.

"At the same time, we also look to capitalise on the success of the Sivers' Wireless business unit and the demand for our leading-edge mmWave beamformer solutions for satellite and 5G, which has gained substantial traction with customers in these developing markets over the last several years, enabling us to create a fully fabless and less capital-intensive company that will remain listed under Sivers Semiconductors AB."

> We believe the potential for AI Photonics is immense yet overshadowed by the equally exciting Sivers´ Wireless business unit. With the attractive opportunity for silicon photonics in AI infrastructure and the emerging demand for photonic biometric sensors, we feel now is the right time to shine a light on this business unit as a standalone entity to gain access to the US capital markets and create an opportunity for our shareholders to participate in its potential future success

European Innovation Council funds QuiX Quantum

The photonic quantum computing company says that its selection by the EIC Accelerator highlights its innovative contributions and will help scale its operations towards its vision of building Europe's leading quantum photonic products

QuiX QUANTUM, a company focused on photonic quantum computing hardware, has been selected by the European Innovation Council (EIC) Accelerator programme, a key initiative of the European Commission.

Being granted the EIC Accelerator highlights QuiX Quantum's innovative contributions and secures financial support for their cutting-edge projects.

The EIC Accelerator programme seeks to identify and support breakthrough technologies with high growth potential. QuiX Quantum says its selection proves its commitment to advancing quantum computing solutions that promise to revolutionise industries globally.

"We are honoured to be chosen for the blended financing of the EIC Accelerator programme which can be up to €17.5 million in combined grant and equity," said Kathy Willing, CFO of QuiX Quantum. "This funding will accelerate our research and development, bringing us closer to realizing the full potential of photonic quantum computing."

Stefan Hengesbach, CEO of QuiX Quantum, added: "I personally consider the EIC Accelerator to be an essential instrument for financing deep tech, high-risk start-ups that are strategically relevant in the EU. The Accelerator will allow us to push our objectives and vision of building Europe's leading quantum photonic products."

QuiX Quantum will receive a blend of grants and equity investments, part of the €411 million allocated to 68 innovative companies across Europe. The company says this funding will enhance its ability to scale its operations, develop new technologies, and attract further investments.

Intel and Source Photonics partner on 800G transceivers

SOURCE PHOTONICS and Intel have entered into a licensing agreement that allows Source Photonics to utilise Intel's 800G transceiver designs, including Intel's silicon photonics chipset, to immediately enable 800G OSFP transceivers for large-scale datacentre and AI infrastructure deployments.

Source Photonics says that this silicon photonics-based solution, together with its own in-house EML-based 800G transceiver modules, provides customers with access to two separate 800G designs and manufacturing lines within one company, offering increased supply chain security and higher volume capacity.

"We are excited about this collaboration with Intel," said John Wang, CEO of Source Photonics. "Our proven transceiver manufacturing expertise, combined with the high-volume, highly reliable silicon photonics technology from Intel, will create enormous value for our customers."

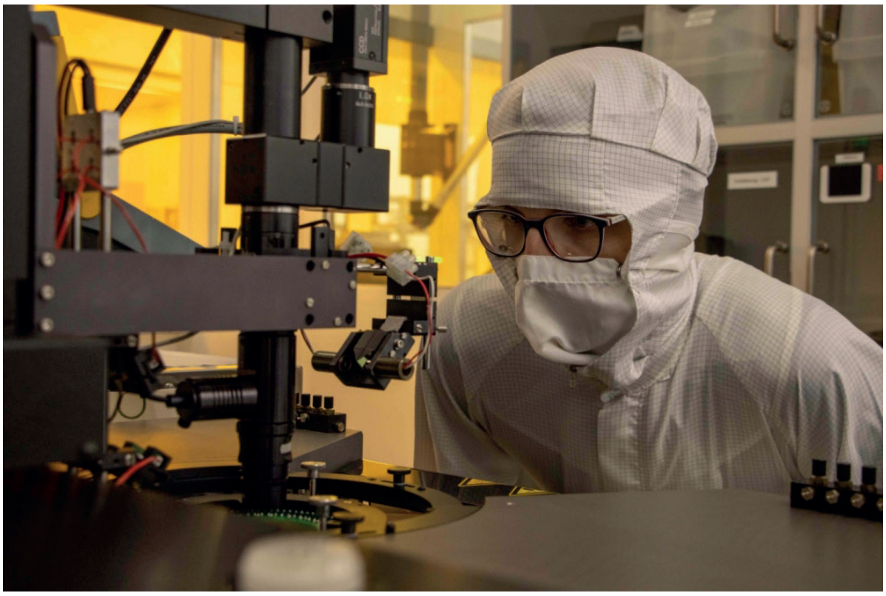
Amit Nagra, VP/GM of Integrated Photonics Solutions at Intel, said: "This collaboration between Intel and Source Photonics to leverage our transceiver design IP and bring to market products using Intel's silicon photonics chipset is a validation of our new strategy."

"As we build upon our strong track record of silicon photonics shipments of over 8 million units to date and continue to develop new silicon photonics technology and products for the datacentre market, collaborations such as this become increasingly relevant."

Fraunhofer IPMS developing near-infrared silicon-based photodiodes

The institute has received government funding for the new project, and hopes it will enable new applications with silicon devices, reducing costs and environmental hazards associated with current near-infrared photodiodes

IMAGE SENSORS and their core component, the photodiode, are indispensable in numerous applications, whether in process, measurement, automotive or safety technology. In the near-infrared range, which is particularly important for many analytical applications, silicon-based photodiodes do not yet offer sufficient sensitivity. Therefore, other materials are used, but they are expensive and sometimes harmful to the environment.



To address this challenge, a new project at the Fraunhofer Institute for Photonic Microsystems (IPMS) aims to develop sensitive silicon-based photodiodes, which are more cost-efficient in production. The Federal Ministry of Education and Research in Germany (BMBF) is funding the MesSi project with €566,000 for a period of three years.

Photodiodes can be found everywhere – as image sensors in cameras inspecting surfaces in process technology or in spectroscopy systems in metrology. In the visible range almost all photodiodes today are made of silicon, as this material is used by default in the semiconductor industry and can therefore be produced more cost-efficiently.

However, in the near-infrared range, not visible to the human eye, silicon-based photodiodes have not been used to date, due to their low sensitivity.

For this reason, materials such as indium gallium arsenide (InGaAs) are used in this range. This material requires its own manufacturing processes however, which are not compatible with silicon semiconductor technology and therefore result in high costs. In addition, heavy metals such as arsenic are used in the manufacturing process. This stands in contradiction to efforts to make the production of microelectronics more environmentally friendly.

Fraunhofer IPMS is pursuing a new research approach to help low-cost silicon photodiodes achieve sufficient sensitivity in the near-infrared. "The innovation is based on the implementation of a new structure in our photodiode," explains project coordinator Michael Müller from Fraunhofer IPMS.

"Instead of the usual planar device topography, we use novel pyramidal and ring structures that function like a light collecting basin. With a very thin metal layer in the Schottky barrier, we increase the internal quantum efficiency – meaning the number of charge carriers generated by light in the semiconductor. We think that these two innovations will significantly increase sensitivity and enable near-infrared applications with silicon photodiodes for the first time."

In the future, silicon photodiodes could enable several new applications in the near-infrared range, particularly in price-sensitive but high-volume markets.

One example is autonomous driving, which requires new LiDAR sensors and fog cameras for effective environmental monitoring. This is particularly important when visibility is obstructed by smoke or fog, which causes optical cameras in the visible range to fail.

Security technology would also benefit from this, with applications ranging from the protection of critical infrastructure to the private sector.

There are also numerous applications in chemical and medical imaging as well as spectroscopy. Hyperspectral imaging in the near-infrared is used in process measurement technology in the pharmaceutical and chemical industries to detect and analyse organic materials and material mixtures.

Intel reveals fully integrated optical I/O chiplet

The company describes its optical compute interconnect chiplet as a revolutionary milestone in integrated photonics technology for high-speed data transmission

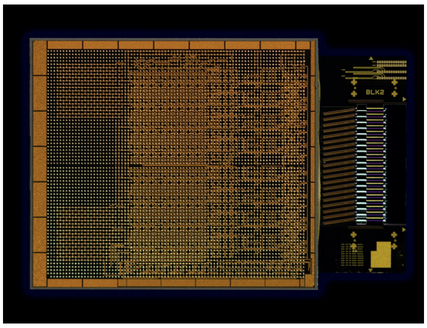
AT THE Optical Fiber Communication Conference (OFC) 2024, Intel's Integrated Photonics Solutions (IPS) Group demonstrated what the company describes as the industry's most advanced and first-ever fully integrated optical compute interconnect (OCI) chiplet co-packaged with an Intel CPU and running live data. Intel says its OCI chiplet represents a leap forward in high-bandwidth interconnect by enabling co-packaged optical input/output (I/O) in emerging AI infrastructure for datacentres and high performance computing (HPC) applications.

The OCI chiplet is designed to support 64 channels of 32G data transmission in each direction on up to 100 metres of fibre optics and Intel expects it to address AI infrastructure's growing demands for higher bandwidth, lower power consumption, and longer reach. The company says it enables future scalability of CPU/GPU cluster connectivity and novel compute architectures, including coherent memory expansion and resource disaggregation.

AI-based applications are increasingly deployed globally, and recent developments in large language models (LLM) and generative AI are accelerating that trend. Larger and more efficient machine learning (ML) models will play a key role in addressing the emerging requirements of AI acceleration workloads.

The need to scale future computing platforms for AI is driving exponential growth in I/O bandwidth and longer reach to support larger processing unit (CPU/GPU/IPU) clusters and architectures with more efficient resource utilisation, such as xPU disaggregation and memory pooling.

Electrical I/O (i.e., copper trace connectivity) supports high bandwidth density and low power, but only offers



short reaches of about one metre or less. Pluggable optical transceiver modules used in datacentres and early AI clusters can increase reach at cost and power levels that are not sustainable with the scaling requirements of AI workloads. According to Intel, a co-packaged xPU optical I/O solution can support higher bandwidths with improved power efficiency, low latency and longer reach – exactly what AI/ML infrastructure scaling requires.

The company says its fully Integrated OCI chiplet leverages its field-proven silicon photonics technology and integrates a silicon PIC, which includes on-chip lasers and optical amplifiers, with an electrical IC. The OCI chiplet demonstrated at OFC was co-packaged with an Intel CPU but can also be integrated with next-generation CPUs, GPUs, IPUs and other system-on-chips (SoCs).

According to Intel, this first OCI implementation supports up to 4T bidirectional data transfer, compatible with peripheral component interconnect express (PCIe) Gen5, while the live optical link demonstration showcases a transmitter (Tx) and receiver (Rx) connection between two CPU platforms over a single-mode fibre (SMF) patch cord.

The company adds that the CPUs generated and measured the optical Bit Error Rate (BER), and the demo showcases the Tx optical spectrum with eight wavelengths at 200 GHz spacing on a single fibre, along with a 32G Tx eye diagram illustrating strong signal quality.

The current chiplet supports 64 channels of 32G data in each direction up to 100 metres (though practical applications may be limited to tens of metres due to time-of-flight latency), utilising eight fibre pairs, each carrying eight DWDM wavelengths, says Intel. The co-packaged solution is also highly energy efficient, consuming only 5 pJ/bit compared to pluggable optical transceiver modules at about 15 pJ/bit, adds the company.

Intel says its main differentiator is unparalleled integration using hybrid laser-on-wafer technology and direct integration, yielding higher reliability and lower costs, and allowing the company to deliver superior performance while maintaining efficiency. Intel adds that its robust, high-volume platform boasts shipping over 8 million PICs with over 32 million integrated on-chip lasers, showing a laser failures-in-time (FIT) rate of less than 0.1. These PICs were packaged in pluggable transceiver modules, deployed in datacentre networks for 100G, 200G, and 400G applications.

Next-generation, 200G/lane PICs to support emerging 800G and 1.6T applications are under development. Intel also says it is implementing a new silicon photonics fab process node with state-of-the-art device performance, higher density, better coupling and vastly improved economics. The company adds that it continues to make advancements in on-chip laser and SOA performance, cost, and power.

Intel's current OCI chiplet is a prototype, and the company is working with select customers to co-package OCI with their SOCs as an optical I/O solution.

ANGELTECH

ESS EXECUTIVE STRATEGY SUMMIT | CS INTERNATIONAL CONFERENCE | PIC INTERNATIONAL CONFERENCE | PE INTERNATIONAL CONFERENCE

Sponsorship / Exhibition / Speaker OPPORTUNITIES AVAILABLE!

Sponsorship, exhibition, and speaker opportunities at PIC International, enable and empower you to educate and penetrate the global photonic integrated circuit industry using a plethora of marketing tools.

Demand is high, with sponsorship, exhibition and speaking slots already being secured for 2025, so to avoid disappointment, please get in touch today.

Delegate Earlybird Discount:

Register before 31 December and get 10% OFF!

Registration to AngelTech allows you to access both days of **PIC International** and the co-located **CS International** and **PE International.**

10% OFF

PLATINUM SPONSORS

Ansys, EVG, ficonTEC (photonics assembly & testing), imec (embracing a better life), KEYSIGHT, LIGHTIUM (CRAFTING LIGHT, SHAPING THE FUTURE), LUCEDA PHOTONICS, PhotonDelta, PICadvanced, scia systems, vanguard AUTOMATION, VIAVI, VPIphotonics

GOLD SPONSORS

ASMPT, CIPOSA, eblanaphotonics, EPIC (EUROPEAN PHOTONICS INDUSTRY CONSORTIUM), Fraunhofer Heinrich Hertz Institute, ISP SYSTEM, OPTICA, set, SMART PHOTONICS

MEDIA PARTNERS

化合物半导体 CS COMPOUND SEMICONDUCTOR CHINA, CS COMPOUND SEMICONDUCTOR, PHOTONICS spectra, PIC PHOTONIC INTEGRATED CIRCUITS, PEW POWER ELECTRONICS WORLD, 半导体芯科技 SS SILICON SEMICONDUCTOR CHINA, SS SILICON SEMICONDUCTOR

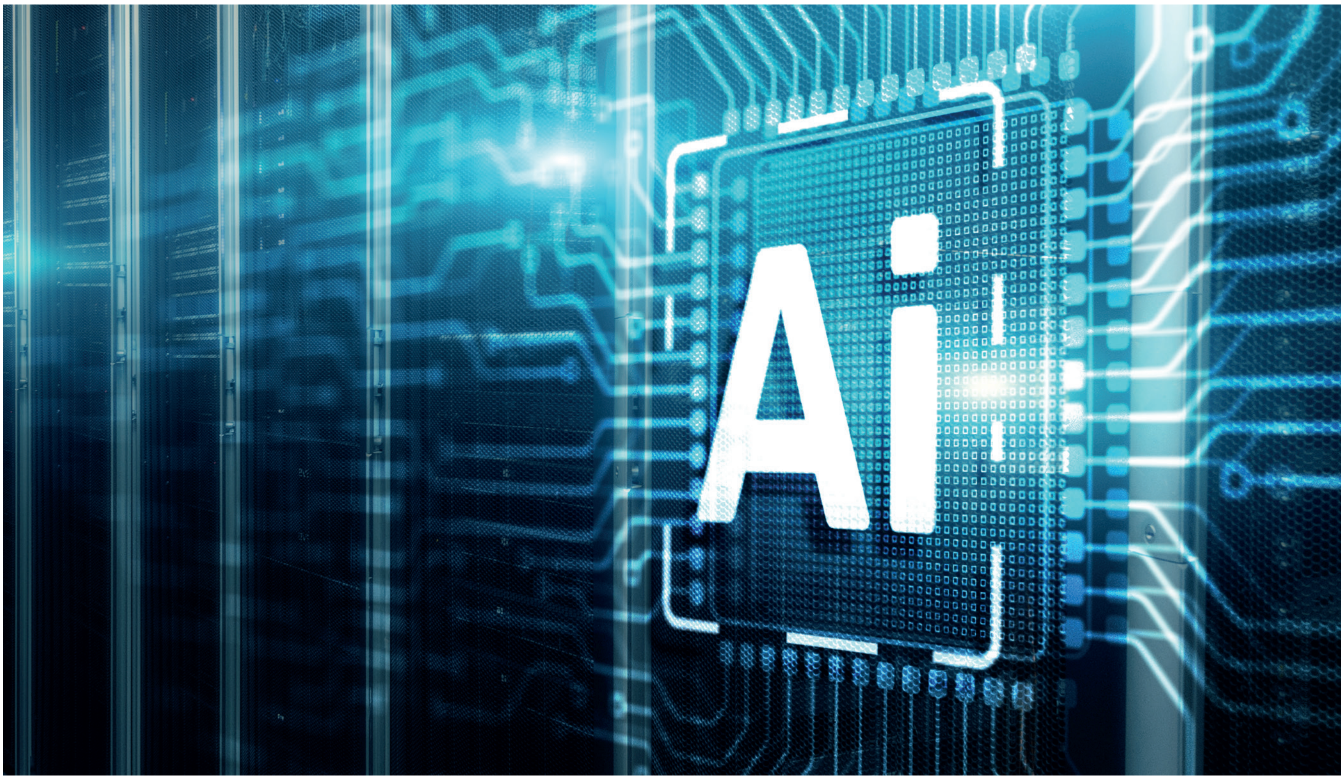
ORGANISERS

Angel BUSINESS COMMUNICATIONS, ANGEL EVENTS

To find out more about our sponsor and speaker opportunities, contact us today on:

+44 (0) 2476 718970
info@picinternational.net
picinternational.net

Angel BUSINESS COMMUNICATIONS | ANGEL EVENTS



Revolutionising optoelectronics with high-precision bonding

As data traffic looks set to outrun conventional pluggable optics, co-packaged optics is a promising innovation for powering our increasingly data-intensive world. However, this technology's performance relies on extreme precision at the manufacturing stage. ASMPT AMICRA's machines can meet this challenge.

BY MARCUS PLANCKH, HIGHTECH COMMUNICATIONS

THANKS TO THE rapid development of AI, the Internet of Things (IoT), 5G, and high-performance computing applications, datacentres have recently seen exponential growth in data traffic. Nearly three quarters of this remains within the confines of the datacentres. Meanwhile, with fibre-optic connections increasingly replacing copper cabling, the market for optical transceivers has been recording double-digit growth rates for several years. It is expected to reach a market volume equivalent to more than €14 billion by 2025. This is hardly surprising; fibre-optic technology has numerous advantages over traditional copper cabling, including saving on raw materials and energy, and offering high-bandwidth, low-loss signal transmission, even over long distances.

Wherever low-loss connections with very high data density are required, fibre optics are already being used today – for backbones in datacentres, for inter-datacentre connections, and for connections to 5G radio masts. Incidentally, besides traditional communications, optoelectronic technology can also be applied to biomedical sensors, augmented reality, power laser and automotive applications. For example, LiDAR, an optical method for measuring distance and speed using lasers, is one of the preferred technologies for 3D obstacle detection for autonomous driving. Many of these applications also require IoT connectivity, and thus additional computing power in datacentres.

In light of these dramatic developments, it is clear that fibre optics with conventional pluggable optics will not be able to keep pace with data communication requirements forever. But co-packaged optics (CPO) is offering a new way of powering today's data-intensive world. The aim of this disruptive technology is to bring optical I/Os as close as possible to the ASIC switch, increasing bandwidth density and energy efficiency. Through advanced packaging and simultaneous optimisation of electronics and photonics, CPO – particularly on the silicon platform – can significantly reduce interconnect lengths, making it a promising technology for future datacentres.

This technology is being refined all the time, with the latest integration approach enabling CPO to use an external laser small form-factor pluggable (ELSFP) as the signal carrier. Laser light sources are placed externally at the faceplate of the SFP, and modulations kept at the CPO, while fibre connections replace the original copper traces. This approach maintains the function of CPO, while isolating heat sources from the core, increasing the feasibility of CPO development and deployment.

High-accuracy requirements

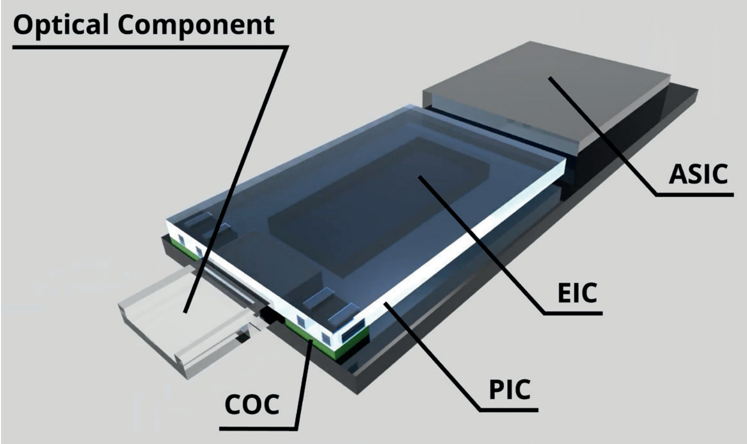
While CPO technology has enormous potential, it also faces challenges. In particular, it demands highly precise control of manufacturing and packaging processes, to ensure seamless connection between electronic and photonic components, as well as stability and reliability under extreme conditions. Standardising CPO technology remains an important industry task to address compatibility issues and drive market applications. For the latest CPO innovations and advanced solutions, ASMPT's precision equipment provides the photonics industry with the means to meet the higher integration demands of CPO.

To send bits through an optical fibre, electrical signals must first be converted into optical signals for transmission, and then converted back again at the end of the path. To do this, light-emitting and light-sensitive components must be connected to each other with such precision that scattering losses and attenuation are kept to an absolute minimum.

Discrete transceivers made up of many components are therefore comparatively large and difficult to produce. For example, each laser diode must be put into operation during assembly to make sure it is aligned correctly – a process also known as active alignment.

Modern semiconductor technologies can already replicate optical components, including waveguides and receivers, on substrates using CMOS lithography. The resulting PICs significantly reduce the number of separate components required for transceivers and therefore also the size and assembly costs. Laser diodes serve as light-emitting components in the optocouplers, which are placed and fixed directly onto the PICs using a die bonder.

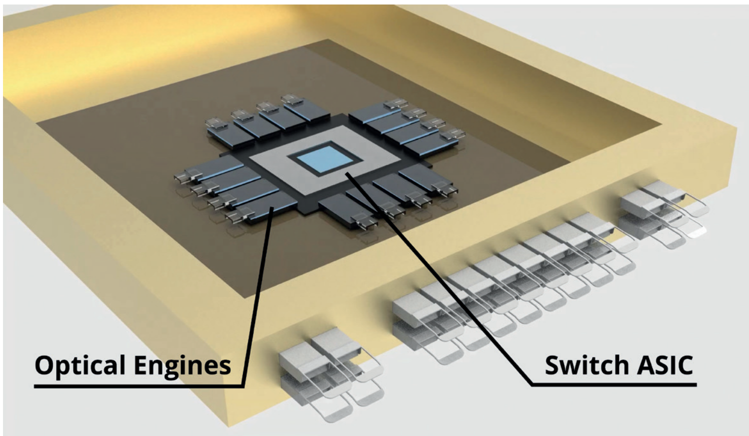
The bonders are normally used in chip production to place semiconductor plates, known as dies, in a housing and to wire or solder them. They work so precisely that active alignment is no longer necessary when placing the laser diode, thus reducing assembly work and increasing fabrication productivity.



➤ Figure 1. Example of a Chip-on-Carrier (COC) embedded in CPO: A laser COC is placed on a PIC wafer together with an electronic IC (EIC). This is then combined with an optical component and the application-specific IC (ASIC) on the substrate to form an optical engine (OE). (Image: ASMPT)

The silicon photonics platform, which offers the greatest possible level of integration of electrical and optical components, requires a new generation of high-precision bonders. For example, a laser diode must be placed with an accuracy of <± 0.5 µm at 3 sigma (where sigma is a measure of process stability that relates extreme values and standard deviation). This is the only way to produce an optocoupler that meets the strict specifications for avoiding light scattering and reflection.

ASMPT, a market leader in this space, has developed such bonders with this high level of precision. With AMICRA, a proven platform is also available for optoelectronics. In fact, the AMICRA NANO model is the first in the industry to achieve a positioning accuracy of <± 0.2 µm at 3 sigma. Due to its unique precision, the AMICRA NANO is used wherever trend-setting, cutting-edge technology is required, including in research, for example. Its



➤ Figure 2. CPO with external laser SFP (ELSFP) as the signal carrier. Laser light sources are placed externally at the faceplate of the SFP, and modulations are kept at the CPO. Fibre connections replace the original copper traces. (Image: ASMPT).

unrivalled accuracy is based on solid technology in multiple senses of the word; the entire positioning unit rests on a heavy, air-sprung granite plate to cushion it against external vibrations. The whole machine weighs around 2.5 tonnes.

Precision placement process

To begin with, the dies to be placed are fed individually or by pre-separated wafer. A very precise vacuum pipette then places them on a wafer or individual substrate. Another unique feature of the machine is that its so-called look-through placement head is designed in such a way that the high-resolution component camera can image the pipette from above. The camera works with a pixel size of 3.45 µm. There are three lenses that recognise line spacings between 1.66 and 5.56 µm.

Next, the pipette grips the die to be applied in such a way that it protrudes slightly on one side. This leaves fiducial marks visible on the die, which the system uses for orientation. There are corresponding fiducials on the substrate, which are also used for exact positioning.

As is usual in surface-mount technology (SMT), the part to be placed is first inspected, and will be rejected if it has visually recognisable defects. Once alignment is complete, the die is placed with a precisely defined bond force of between 0.2-20 N, and then measured again. If the secondary measurement also shows values within the permissible tolerance range, the die is fixed by laser soldering, bonding, or a combination of contact pressure and heat.

The laser soldering step is enhanced by another special feature of the AMICRA NANO: the laser is aimed at the substrate from below through a glass plate. The advantage of this is that the elements are less sensitive to heat on their underside than they are on the top. A resistance heater integrated into the pipette also heats the component, which prevents positioning errors caused by thermal expansion and also improves the soldering behaviour. In total, this highly precise and complex process requires a cycle time of 20-30 seconds. Some manufacturers therefore have 10 or more AMICRA NANOs working in parallel on one store floor. Overall, the process is far more efficient than discrete assembly.

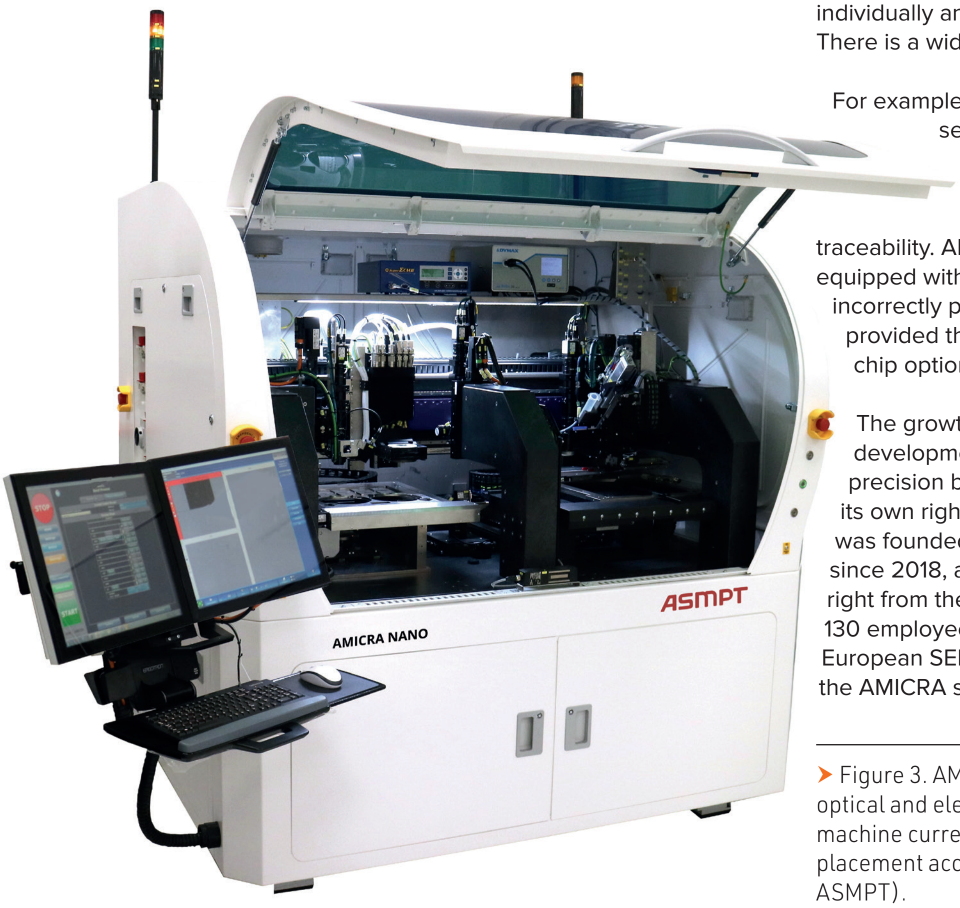
For products with less stringent accuracy requirements, the AMICRA NOVA Pro bonder, also from the AMICRA platform, can offer shorter cycle times and more automation. This machine has a placement accuracy of <± 1 µm at 3 sigma, but significantly shorter cycle times (3-6 seconds at 1.5 µm, and 1.2-1.4 seconds at 5 µm). These machines also have great potential, due to the very wide range of CPO applications mentioned earlier.

Customised solutions

Today, no two electronics products have the same fabrication process. For this reason, the high-precision die bonders are generally designed individually and tailored to customer specifications. There is a wide range of options for customisation.

For example, software is available that can seamlessly trace all processed parts. This is particularly important to automotive suppliers, whose customers demand absolute traceability. AMICRA machines can also be equipped with a repair function that removes incorrectly positioned parts from the substrate, provided that this is technically possible. A flip-chip option is also part of the portfolio.

The growth of AMICRA's research and development department shows that high-precision bonding is now almost an industry in its own right. The Regensburg-based company was founded in 2001, has been part of ASMPT since 2018, and has enjoyed a steep growth curve right from the start. It currently has more than 130 employees. Last year, ASMPT opened its first European SEMI Center of Competence (CoC), at the AMICRA site in Regensburg, further supporting



➤ Figure 3. AMICRA NANO: The bonder for processing optical and electronic components. The most precise machine currently on the market operates with a placement accuracy of <± 0.2 µm at 3 sigma. (Image: ASMPT).

R&D by providing specialists and taking care of tests and evaluations.

With its market-leading machines, ASMPT is the only manufacturer to cover the entire process chain from wafer to assembled printed circuit board, and operates a large global network of R&D centres. These modern, pioneering laboratories have the latest machinery and equipment to demonstrate technologies and investigate the precise impact that innovations will have on electronics manufacturing, especially for CPO.

Dr. Johann Weinhändler, Managing Director at ASMPT AMICRA, sees the benefits of the CoC not least in the regional context: "We are delighted that we can now offer leading semiconductor companies and decision-makers in Europe the innovative ASMPT Semiconductor solutions and expertise at our centrally located CoC in Germany," he says.

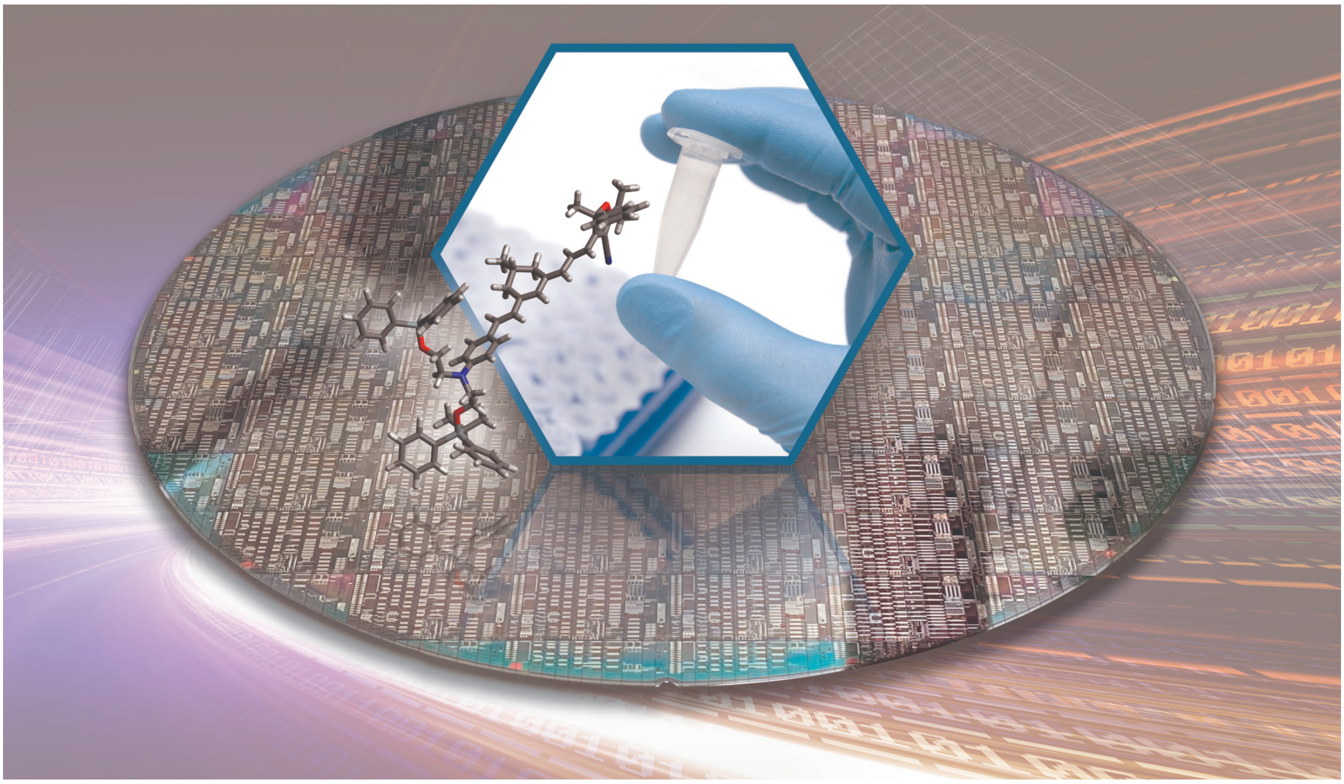
Dr. Weinhändler also points out that there are many reasons to be optimistic for the future: "The cloud market is growing infinitely. The demand for fast data rates and innovative applications is rising sharply, for example in datacentres. This goes as far as latency-free real-time transmissions. The situation is similar in future markets such as autonomous driving. Companies in this sector need ever smaller sensors and new technologies, just think of LiDAR.

However, this market also has enormous potential for us because it requires additional transmission stations almost everywhere, as every traffic light needs to be networked. These developments are fuelling our business with photonics and therefore systems for ultra-high-precision assembly."

The synthesis of optics and electronics marks a quantum leap, especially in communication technology, but also in many applications beyond it. High integration density in production is becoming increasingly important; the closer that components are brought together and the fewer individual parts need to be assembled per unit, the more effective, cheaper, and energy-efficient the product will be.

However, to achieve the next level of integration of the key technologies of silicon photonics and CPO, it is essential that production technologies also advance to new heights in precision and process stability. The AMICRA platform is already demonstrating the direction in which development must go. Machines such as the AMICRA NANO are setting standards that the industry must continue to follow in the future.

Dr. Johann Weinhändler, Managing Director at ASMPT AMICRA GmbH in Regensburg, is responsible for the Semiconductor Solutions Segment of ASMPT in EMEA. He is convinced that "the market for photonics and therefore for ultra-precise placement solutions will continue to grow enormously." (Image: ASMPT).



Silicon-organic hybrid slot waveguide modulators on the verge of industrial adoption

Complementing highly scalable silicon photonics with engineered organic materials offers a path towards optical transceivers with unprecedented performance and efficiency. Recent data proves the photochemical stability of silicon-organic hybrid devices at practically relevant power levels, removing the last roadblock to industrial adoption.

BY ADRIAN MERTENS, CARSTEN ESCHENBAUM, AND CHRISTIAN KOOS AT SILORIX

GENERATIVE ARTIFICIAL INTELLIGENCE (AI) is about to fundamentally transform our world, penetrating virtually every domain of modern life – from healthcare and diagnostics to industrial design and optimised production to stunningly realistic art, to name just a few. On a technical level, generative AI crucially relies on specific types of neural networks such as large language models (LLMs), which have tens of billions or even hundreds of billions of free parameters and which are designed to process and emulate human text or other content based on vast amounts of training data.

Training LLMs is a grand computational challenge, requiring massively parallel processing in dedicated AI clusters that contain thousands of highly specialised computing nodes, such as graphics processing units (GPUs) or tensor processing units (TPUs). However, scaling AI clusters – and hence the performance of associated LLMs – beyond current sizes is becoming increasingly difficult, primarily due to interconnect bottlenecks that limit the data transfer among the various computing nodes. Overcoming these bottlenecks is key to building even larger AI models that can take performance to yet another level.

In this context, it is widely accepted that massively parallel optical transmission will play an essential role, but current optical transceiver technology is still struggling to cope with the tough scalability and reliability challenges of AI clusters. In previous years, silicon photonics has emerged as a mainstay for cost-efficient mass production of optoelectronic devices and systems. However, conventional silicon photonic transceivers are fundamentally limited by

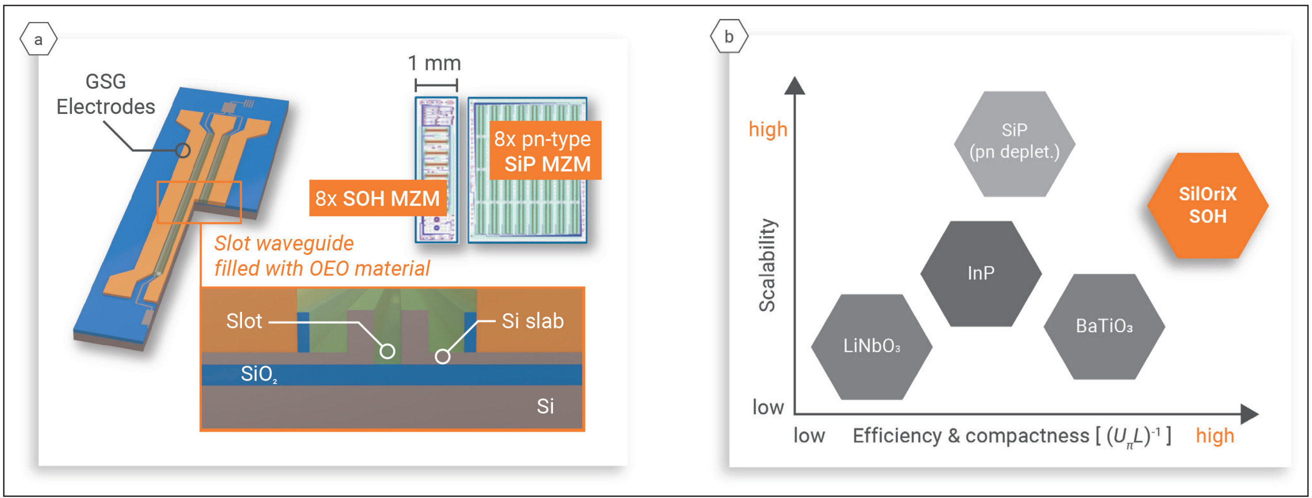


Figure 1. Concept and performance of SilOriX's silicon-organic hybrid (SOH) technology, combining established silicon photonics with highly efficient organic electro-optic (OEO) materials. (a) Basic concept of an SOH Mach-Zehnder modulator (MZM). The device comprises a silicon photonic slot waveguide in each arm, covered with an organic electro-optic (OEO) material. Appropriate poling of the OEO material leads to highly efficient chirp-free push-pull operation at ultra-low π-voltage length products $U_\pi L < 0.5$ Vmm. Upper right: Footprint of 8 x 200G = 1.6T transmitter blocks, implemented by SOH MZM (left) and by standard pn-type silicon photonic MZM (right). (b) Benchmarking of SOH slot waveguide modulators with respect to competing technologies, in terms of efficiency & compactness and scalability. SOH devices can rely on highly scalable silicon photonic base structures that can be efficiently mass-produced, while the OEO material is applied in wafer-level post-processing steps (see Figure 4).

the properties of silicon as the underlying functional material system. These limitations are becoming increasingly obvious in light of established and emerging transceiver standards with interface rates between 1.6T-12.8T [1]. One of the key requirements in optical transceiver technology is therefore to improve the performance scalability of silicon photonic transmitter circuits while maintaining their amenability to cost-efficient mass production.

Silicon-organic hybrid (SOH) slot-waveguide modulators

One of the primary limitations of conventional silicon photonics is the absence of Pockels-type optical nonlinearities – a direct consequence of the centrosymmetry of the silicon crystal lattice.

For this reason, conventional silicon-photonic modulators must rely on free-carrier injection and depletion via corresponding diode structures that are integrated into the waveguide core. This leads to comparatively low modulation efficiency, limited modulation speed, and unavoidable coupling of amplitude and phase modulation.

Silicon-organic hybrid (SOH) devices overcome these problems by combining silicon photonic waveguide structures with highly efficient organic electro-optic (OEO) materials, for which an ultra-high in-device Pockels coefficient of 390 pm/V has been obtained by theory-driven molecular design [2]. Figure 1(a) shows the basic concept of an SOH Mach-Zehnder modulator (MZM), where each arm contains a silicon photonic slot waveguide that is filled with the OEO material. The slot-waveguide structure increases the interaction between the guided light and the OEO cladding. The electrical signal is applied via a millimetre-wave transmission line, here illustrated in ground-signal-ground (GSG) configuration, which is connected to the doped rails of the slot via thin silicon slabs.

Appropriate poling of the OEO material allows for highly efficient chirp-free push-pull operation at ultra-low π-voltage length products, $U_\pi L < 0.5$ Vmm. This leads to ultra-compact devices with sub-millimetre lengths that can be operated with drive signals of a few hundred millivolts peak-to-peak swing, thus paving a path towards efficient linear-drive operation by standard CMOS circuitry.

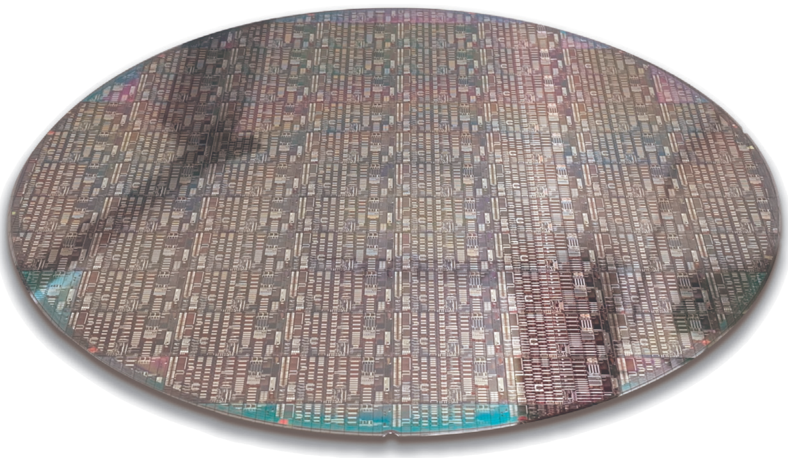


Figure 2. An 8-inch SOH wafer fabricated by SilOriX and its partners, carrying more than 25,000 SOH modulators along with a wide range of high-end silicon photonic circuits for various applications in optical communications, ultra-broadband signal processing, and optical metrology.

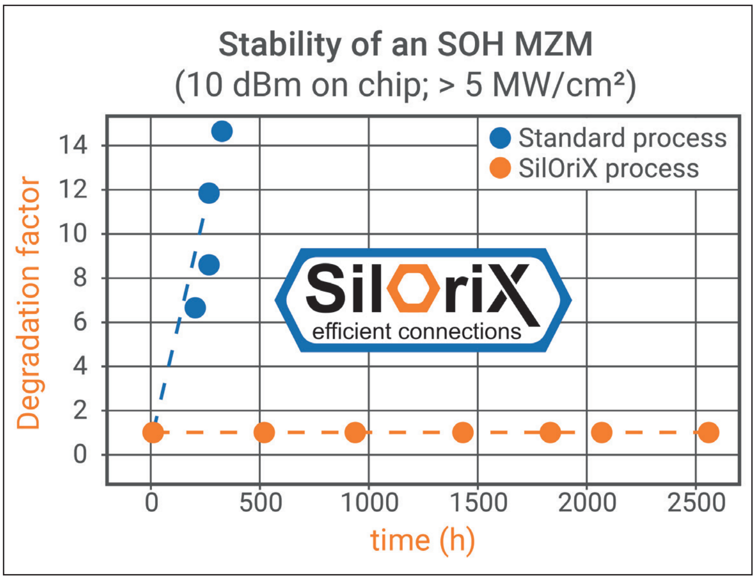


Figure 3. Long-term photostability test of SilOriX SOH MZM. By intimate combination of material, process, and device development, SilOriX has managed to eliminate stability problems in its SOH devices, that were long perceived a roadblock towards industrial exploitation of the technology. The devices under test were operated for more than 2500 hours at an on-chip power of 10 mW, without any sign of photodegradation.

Figure 1(b) benchmarks SOH slot waveguide modulators with respect to competing technologies. SOH devices can rely on highly scalable silicon photonic base structures, which can be seamlessly co-integrated with the wealth of existing silicon photonic devices without any change to the front-end-of-line processes. The functional OEO cladding is then applied by efficient wafer-level post-processing without interfering with any front-end-of-line steps (see Figure 5). SOH technology is therefore amenable to cost-efficient mass production, just like conventional silicon photonics, while providing electro-optic modulators with ultra-low $U_\pi L$ products and hence record-high efficiency. Plasmonic-organic hybrid (POH) devices are subject to rather high optical losses and are therefore not included in Figure 1(c), despite having unparalleled modulation speed [3]. The upper right of Figure 1(a) also illustrates the compact footprint of SOH devices, even in direct comparison to conventional silicon photonic modulators, and emphasises the scalability and integration density of SOH devices once more. Figure 2 shows an 8-inch SOH wafer fabricated by SilOriX and its partners, carrying more than 25,000 SOH modulators along with a wide range of high-end silicon photonic circuits for various applications in optical communications, ultra-broadband signal processing, and optical metrology.

SOH processing and photochemical stability

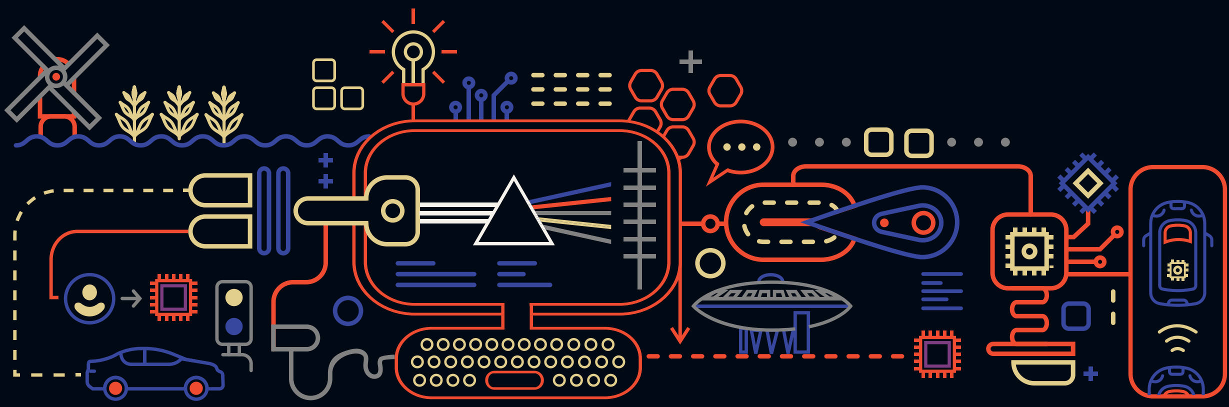
A series of research demonstrations has proven the outstanding performance of SOH devices, but industrial adoption has so far been hindered by a lack of proven long-term stability of the underlying OEO materials [2]. The processes behind OEO degradation can be largely subdivided into two mechanisms. One mechanism is de-poling, i.e. the loss of preferential alignment of the functional OEO groups (“chromophores”), which is established in a one-time poling process during device fabrication. The other mechanism is photochemical degradation of the chromophores under high optical intensities. It has previously been demonstrated that the problem of de-poling can be overcome either by using materials with high glass-transition temperature [5], permitting long-term stability at 85 degrees Celsius, or by cross-linking of the organic matrix after poling [6], through which operation temperatures of 120 degrees Celsius can be reached.

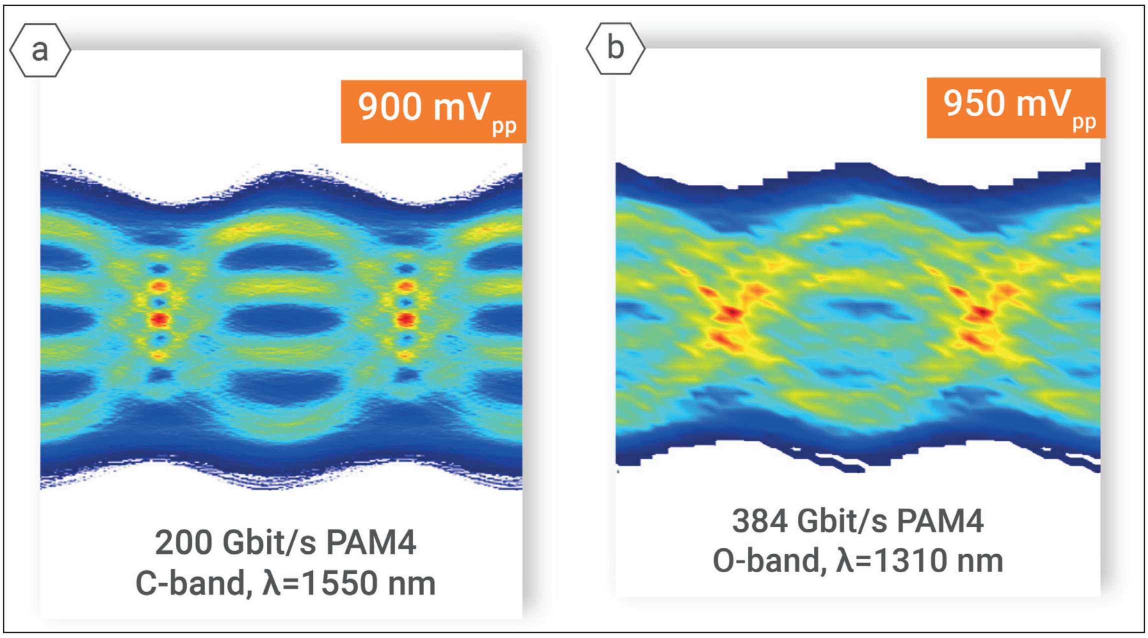
In contrast, photochemical stability has continued to pose a challenge. However, there is another industry we can learn from. It turns out that the main mechanism responsible for photochemical degradation is just the same as the one that led to lifetime limitations of early-stage optical light-emitting diodes (OLEDs). This process involves optical excitation and the subsequent reaction of an organic chromophore with ambient oxygen, leading to a highly reactive singlet oxygen molecule, which can then chemically attack the functional group of the chromophore in a further reaction [7].

This insight points towards a solution: dedicated processing paths combined with appropriate device architectures and chip-level sealing techniques – just like in state-of-the-art OLED displays. Still, the extraordinarily high optical intensities in SOH devices represent a major problem. Specifically, the strong confinement of the guided light in the slot waveguide, which enhances the interaction with the OEO material, and which is key to the outstanding device efficiencies, unavoidably leads to large optical intensities in the slot region.

Assuming a wavelength of 1550 nm and an optical power of 10 mW propagating in a typical slot waveguide, the intensity in the slot region can easily reach values of the order of 5 MW/cm^2, which corresponds to approximately 1000 times the optical intensity on the surface of the sun! Such high intensities do not occur in conventional PICs and are therefore not covered by current reliability standards and test protocols. This might also be the reason why previous stability tests of SOH devices have only been performed at comparatively low intensities of, for example, 500 kW/cm^2 [8] – roughly an order of magnitude below the intensities that can be expected in practical applications.

Despite these immense challenges, SilOriX has overcome photodegradation of its SOH devices, through the joint development of materials, device architectures, and processing paths along with consequent testing at practically relevant intensity levels. This work has removed the last fundamental roadblock towards industrial exploitation of SOH technology.



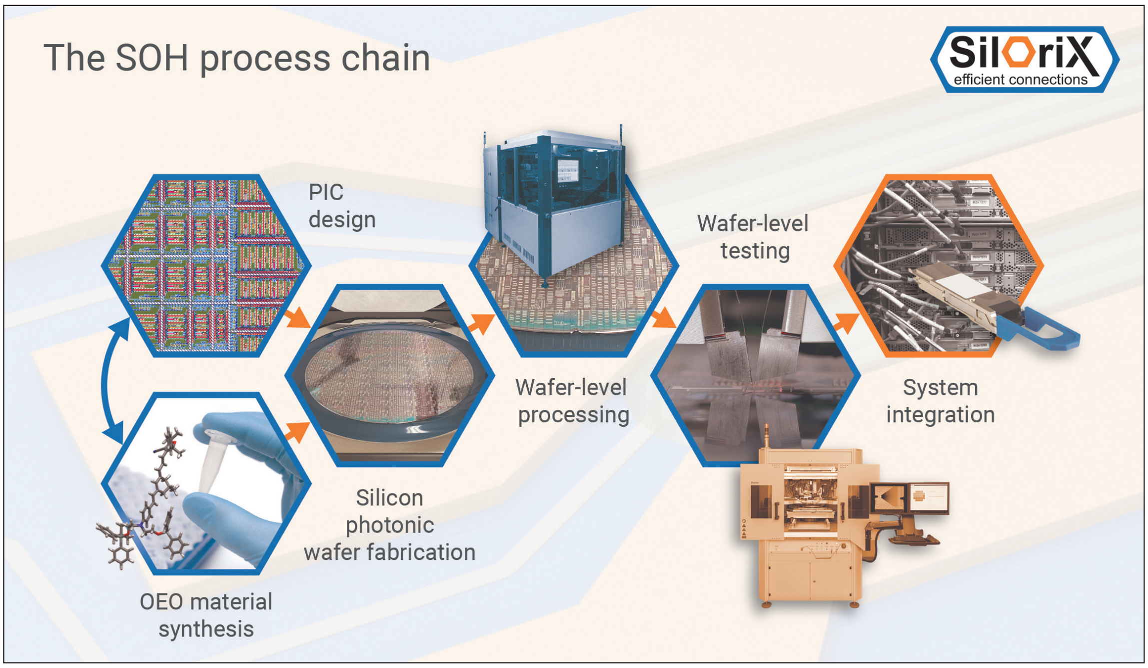


➤ Figure 4. (a) 100 GBaud PAM-4 (200G) eye diagram of a packaged C-band SOH modulator. (b) 192 GBaud PAM-4 (384G) eye diagram generated in an O-band proof-of-concept experiment of SilOriX and its partners [4].

Figure 3 shows the test data of a packaged C-band (λ = 1550 nm) device, operated with an on-chip power of 10 mW per slot waveguide. The vertical axis corresponds to the degradation factor $p = U_\pi(t)/U_\pi(t{=}0)$, indicating the relative increase of the π-voltage U_π over testing time t, relative to the beginning of the experiment (t = 0). The devices under test were operated for more than 2500 hours without showing any sign of photodegradation, thus paving the way for industrial application of long-term-stable SOH devices. We can infer the importance of the exact processing path from the strongly accelerated degradation of devices produced through non-optimised processes, indicated by the blue line in Figure 3.

What's next?

Based on the demonstration of long-term-stable SOH devices (Figure 3), SilOriX is now establishing a dedicated SOH technology platform that builds upon a combination of proprietary device concepts, OEO materials, and processing workflows (Figure 5).



➤ Figure 5. SilOriX's SOH process chain. The SOH process starts with PIC design and synthesis of dedicated organic electro-optic (OEO) materials. After the fabrication of the PICs in commercial silicon photonic foundries, the OEO materials are applied on wafer-scale via highly efficient processes like inkjet printing, utilising industry-standard equipment (e.g. the "n.jet semicon" by Notion Systems). The fully functionalised SOH wafers are then characterised and diced. Known-good SOH dies with outstanding performance can finally be integrated into optical transceiver systems.

Fundamental to this process chain is maintaining compatibility with wafer-level mass production, using, for instance, inkjet printing for material deposition and wafer-level testing for performance verification. Notably, OEO material deposition is exclusively done by post-processing and thus does not affect foundry-specific highly optimised silicon photonic fabrication processes.

Building upon this process chain, SilOriX is now starting to engage with industrial partners to transfer its SOH technology into commercial products. A major focus is on high-performance optical transceivers for intensity modulation and direct detection, which could be crucial for next-generation AI clusters. In this context, SilOriX is currently concentrating its efforts on transferring the technology from the telecommunication C-band (λ = 1530-1565 nm) and L-band (λ = 1565-1625 nm) to the O-band (λ = 1260-1360 nm), where chromatic dispersion is much less of an issue. SilOriX, together with Karlsruhe Institute of Technology (KIT), recently demonstrated the potential of SOH O-band modulators in a proof-of-concept experiment leading to a line rate of 384G transmitted by four-state pulse-amplitude modulation (PAM-4) in a single SOH-MZM (Figure 4(b)) [4]. This demonstration brings single-wavelength line rates of 400G or more within reach, which could greatly simplify the architectures of future 3.2T, 6.4T, or 12.8T Ethernet transceivers.

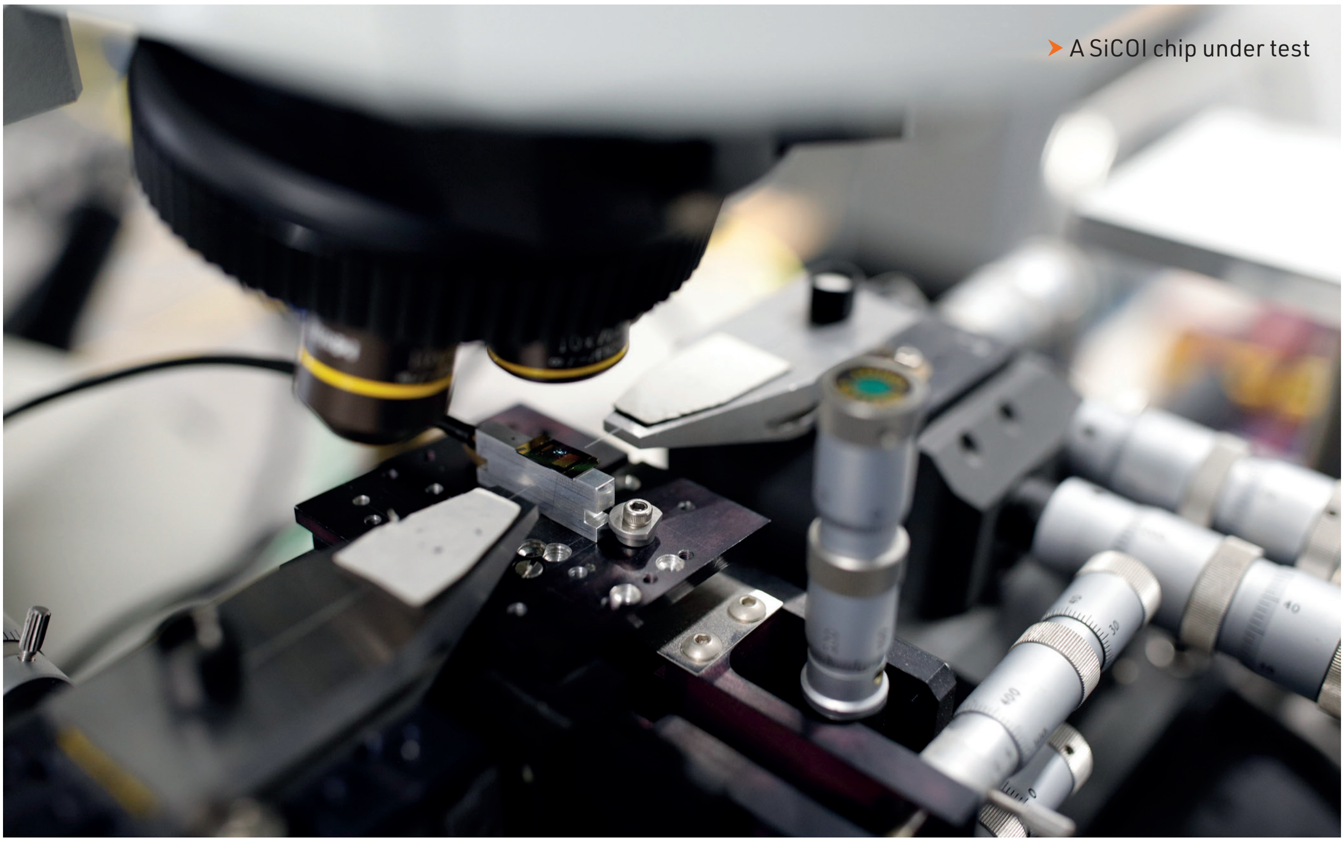
The voltage swing utilised for this transmission experiment was still below 1 V_{pp}, emphasising again the outstanding efficiency of SOH modulators. More specifically, SOH modulators can be driven directly with signals with sub-1 V_{pp} swing, which can be efficiently generated by CMOS circuits, thus significantly reducing the complexity and the power dissipation of the respective transceiver module. SilOriX has showcased this feature of their SOH modulators in live demonstrations at several conference exhibitions, for example, by driving a packaged MZM directly with the CMOS outputs of an industry-standard SerDes die, which provided 112G PAM-4 signals with 300 mV_{pp} peak-to-peak swings [9]. By employing more sophisticated equipment and slightly higher swings, the SOH device demonstrated data rates of 200G PAM-4 (Figure 4(a)).

Note that the excellent performance of SOH modulators is not limited to intensity modulation and direct detection but can also be leveraged for coherent communications [2] – another interesting target application of SilOriX's SOH technology. Moreover, SOH devices have recently been demonstrated to support cryogenic operation at temperatures of just a few Kelvin. Such devices might be instrumental to optical egress links that connect superconducting digital circuits or quantum processors at cryogenic temperature levels to their room-temperature environment [10].

Further application fields of ultra-efficient SOH phase shifters may emerge in the context of programmable photonics, ultra-broadband signal processing, or optical metrology and sensing. Just as happened with OLEDs in the past, we believe that SOH technology is now on the verge of entering industrial applications with tremendous potential, after having kept a low profile in academic research for over a decade.

FURTHER READING / REFERENCE

- [1] Ethernet alliance, „https://ethernetalliance.Org," available: https://ethernetalliance.Org/technology/ethernet-roadmap/.
- [2] W. Freude et al., "High-performance modulators employing organic electro-optic materials on the silicon platform," in ieee journal of selected topics in quantum electronics, vol. 30, No. 4, Pp. 1-22, 2024 , Doi: 10.1109/Jstqe.2024.3385375.
- [3] M. Burla, et al., „500 Ghz plasmonic mach-zehnder modulator enabling sub-thz microwave photonics." Apl photonics 1 may 2019; 4 (5): 056106. Https://doi.Org/10.1063/1.5086868
- [4] A. Schwarzenberger et al., „O-band soh mach-zehnder modulator operating at a pam4 line rate of 384 gbit/s with sub-volt drive voltage," in optical fiber communication conference (ofc), post-deadline-session th4b.6, San diego, usa, 2024.
- [5] C. Eschenbaum et al., „Thermally stable silicon-organic hybrid (soh) mach-zehnder modulator for 140 gbd pam4 transmission with sub-1 v drive signals," in european conference on optical communication (ecoc), post-deadline-session th3b.2, Basel, swiss, 2022.
- [6] A. Schwarzenberger et al., „First demonstration of a silicon-organic hybrid (soh) modulator based on a long-term-stable crosslinked electro-optic material," in european conference on optical communications (ecoc), we.A.4.2, Glasgow, uk, 2023.
- [7] Y. Tominari et al., „Photostability of organic electro-optic polymer under practical high intensity continuous-wave 1550 nm laser irradiation," j. Appl. Phys, vol. 60, P. 101002, 2021.
- [8] M. Lebby, „high speed, low power, tiny modulators in a polymer pic platform are poised to enable 800g/1.6tbps data communications, driven in part by artificial intelligence," in pic international conference 2024, brussels, 2024.
- [9] A. Schwarzenberger et al., „Linear-drive amplifier-less 112 gbit/s pam4 operation of a silicon-organic hybrid (soh) mach-zehnder modulator at 265 mvpp," in optical fiber communication conference (ofc), m3k.6, San diego, usa, 2024.
- [10] A. Schwarzenberger et al., „First demonstration of a cryogenic silicon organic hybrid (soh) mach-zehnder modulator with a sub-1v π-voltage", in conference on lasers & electro-optics (cleo), sth5c.7, San jose, usa, 2023.



A SiCOI chip under test

Integrated photonic platforms:
The case for SiC

The potential of SiC integrated photonics is starting to be unleashed, thanks to the unique photonic properties of this material and the development of high-quality epitaxial growth

BY HAIYAN OU FROM THE TECHNICAL UNIVERSITY OF DENMARK

THE MOST mature and applied semiconductor ever, silicon, is the pillar for modern microelectronics. For the last 50 years or more it has been revolutionising human life, with progress in computation prowess spurred on by adherence to Moore Law, leveraging planar processing.

However, the shrinking of device dimensions cannot continue forever. Line widths are now approaching their physical limit, leading those at the forefront of this technology to search for a way forward to address the looming bottleneck. One promising option involves turning to integrated photonics.

Electrons versus photons

A crucial difference between integrated electronics and integrated photonics is the carrier. Evaluated in this regard, the latter has much appeal. The merits of the photon include: an absence of charge, preventing interference from electromagnetic fields; and an absence of mass, enabling devices to operate at far faster speeds than their electronic counterparts (see Table 1). However, there are challenges in the photonic domain, including the manipulation of this carrier.

In integrated electronics, silicon dominates. Meanwhile, in integrated photonics multiple material platforms co-exist, including silicon, Si_3N_4, GaAs, InP, GaP, AlN, $LiNbO_3$ and SiC. This high level of diversity reflects the fact that no single material provides the six basic building blocks for an integrated photonic chip: a light source, a waveguide, a modulator, detection, low-cost assembly and intelligence.

Silicon is playing a very active role in photonics, thanks to a well-developed material and its mature processing, refined over many decades of manufacture of integrated electronics. However, silicon has two significant drawbacks. The first is that it

	Photons	Electrons
Mass	0	9×10^{-31} kg
Charge	0	-1.6×10^{-19} Coulombs
Speed	3.0×10^8 m/s	0, or less than 3.0×10^8 m/s
Spin	1	Half
Antiparticle	None	positrons

➤ Table 1. Comparison of photons and electrons

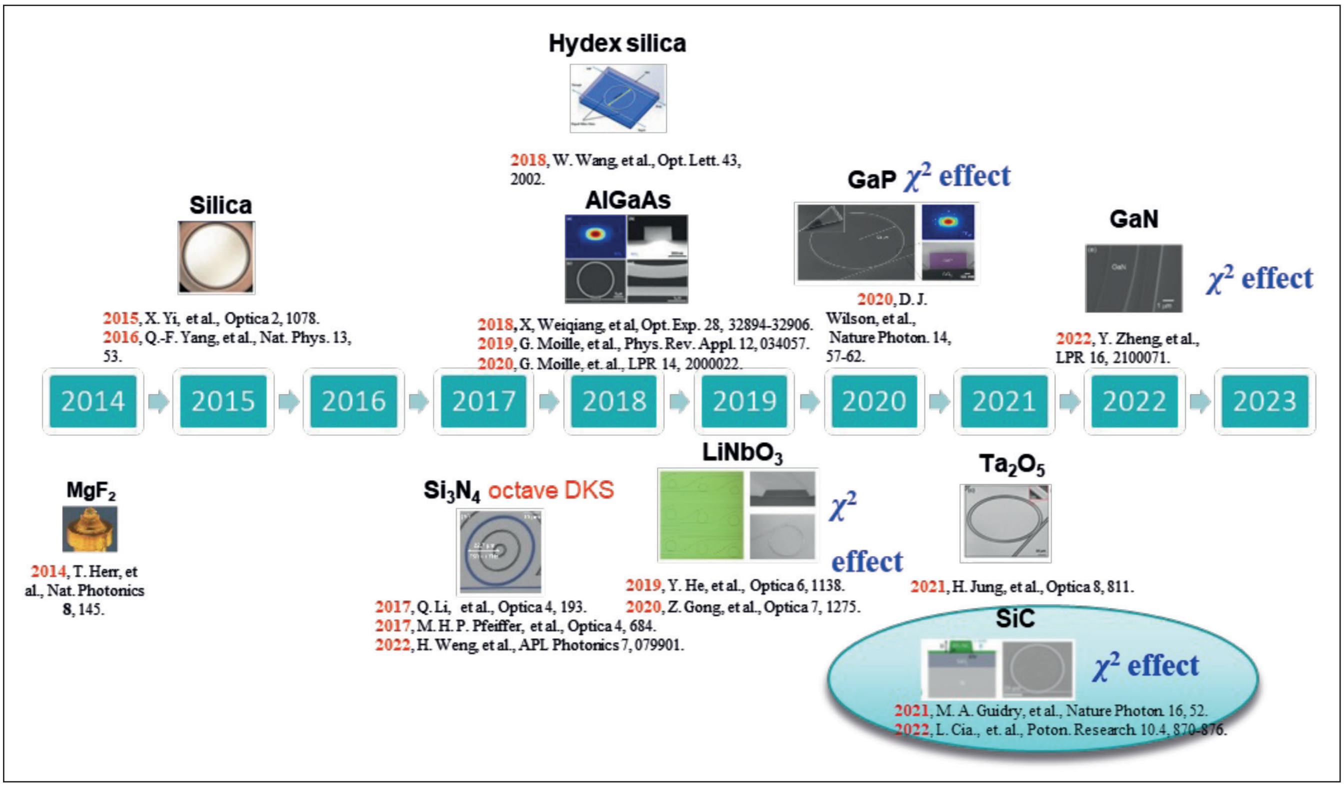
is an indirect bandgap semiconductor, so is inherently inefficient for light emission; and the second is that due to a bandgap of 1.12 eV, strong two-photon absorption occurs at telecommunication wavelengths, screening other nonlinearities, such as four-wave mixing, which provides wavelength conversion.

These two restraints create opportunities for other materials, such as III-Vs and wide bandgap semiconductors. For example, direct bandgap III-V semiconductors are ideal for integrated lasers solutions, while wide bandgap semiconductors have negligible two-photon-absorption within the telecommunication wavelength range.

SiC: Pros and cons

Within this family of compound semiconductors, SiC is emerging as a very promising candidate for integrated photonics. This wide bandgap material has many strengths, including being CMOS compatible, bio-compatible, abundant, non-toxic and thus sustainable; and it has unique photonic properties, such as both high second-order and third-order nonlinearities, a high refractive index, a wide bandgap, and a low intrinsic material loss. Additional strengths include having more than 250 polytypes with variable properties, a thermal conductivity that's more than three times that of silicon, and stable mechanical, physical and chemical characteristics. Furthermore, the processing of SiC is advanced – there is a mature growth technology for producing high crystal-quality SiC, engineers know how to dope this material, and mature material growth and device fabrication has already been established for SiC power electronics, laying the foundation for efforts to scale SiC in integrated photonics.

The wide adoption of SiC power devices, particular in electric vehicles, has laid a solid foundation for the deployment of this material system in SiC photonics. However, despite these advances in materials and fabrication, three substantial challenges have to be addressed: the formation of SiC-on-insulator (SiCOI) stacks, in order to confine



➤ Figure 1. The microcomb development roadmap.

Table 2: Comparison of SiC with other material platforms in integrated photonics.

Material	n	2nd NL (pm/V)	3rd NL (m^2/W)	Bandgap (eV)	Loss (dB/cm)
Si	3.5	0.6	6.7×10^{-18}	1.12	0.3
SiO_2	1.4	0	3×10^{-20}	9	0.06
MgF_2	1.38	0	9×10^{-21}	10	
Si_3N_4	2	0.3	2.4×10^{-19}	5	0.07
SiON	1.8	0	7×10^{-20}		0.06
AlN	2.1	1	2.3×10^{-19}	6	0.6
Ta_2O_5	2.1	0.34	7.23×10^{-19}	3.8	0.3
$LiNbO_3$	2.2	27		4	0.027
AlGaAs	3.3	0	2.6×10^{-17}	1.4-2	1.4
GaP	3.1	82	1.2×10^{-17}	2.26	1.2
SiC	2.6	50	8.6×10^{-19}	2.4-3.3	0.08

the light in SiC; the development of nanofabrication technology, for low loss and dispersion control; and the introduction of an efficient coupling scheme for the coupling of light in and out of a chip.

In photonic circuits, the path of the photon is controlled by the waveguide, using total internal reflection to steer light through the structure. To ensure that photons are confined within a SiC layer, this material is embedded in low refractive index material, such as SiO_2. Commercially available SiC tends to be in the form of wafers, typically 500 μm-thick, while the SiC layer in a SiCOI stack is normally less than 1 μm.

The first big challenge to address is to transfer SiC from a wafer to a thin layer. Our team at the Technical University of Denmark initially took on this challenge with an ion-cut method, also known as smart cut, well established for the production of SOI wafers. Unfortunately, this approach led to a high optical loss of around 6 dB/cm, resulting from ion implantation.

This loss could not be reduced dramatically by thermal annealing, due to limitations associated with the lower melting temperature of the silicon substrate. One possible solution might be to turn to laser annealing, rather than furnace annealing, as this source can be focused to a small spot, allowing just the SiC layer to experience a high temperature for defect recovery, while maintaining the silicon substrate below its melting point.
Our current approach differs from this. We avoid ion implantation altogether, using a bonding and grinding method to form our SiCOI structures. However, the yield is still very low.

Another concern is waveguide loss, resulting from imperfections in fabrication. If there is any roughness at the surface of the SiC waveguide, this increases its loss. To minimise this we have optimised our SiC waveguide fabrication process, which consists of electron-beam lithography, dry etching and top-cladding SiO_2 deposition. This approach enables us to form SiC waveguides with a well-defined geometry and a smooth surface.

A typical cross-sectional geometry of our SiC waveguides is around 500 nm by 500 nm. While this is much bigger than the feature size of a FET, the transistor used to control electron transport in ICs, it is still much smaller than a spot size from a standard single mode fibre – that's around 10 μm. Due to this significant difference in size, we have devoted much effort to ensuring efficient light coupling between a standard single-mode fibre and a SiC waveguide, using mode conversion on the chip. We also aim to achieve extremely low loss within the waveguide, so that we don't need an on-chip amplifier, a device that doesn't exist yet.

To test our SiC optical chips, we use a high magnification microscope to aid the alignment of SiC waveguides and optical fibres (see opening image). This task is supported by mounting the optical chip and the fibre ends on three-dimensional adjustable stages.

Optical frequency combs

Back in 2005, the Nobel Prize in physics went to pioneers in the field of optics. Roy Glauber won half the award for his contribution to the quantum theory of optical coherence, and the other half was shared by John Hall and Theodor Hänsch, for their contribution to the development of laser-based precision spectroscopy, including the optical frequency comb (OFC) technique. An OFC produces a spectrum with discrete, distinct, and equally spaced frequency lines – it is like a ruler for measuring light frequencies.

The chip-scale frequency comb, also called a microcomb, represents the third generation of OFC. It follows the mode-locked laser OFC, the first generation of this technology, and the more recent fibre laser OFC, the second generation of this technology. Combining the advances of nanofabrication and nonlinear optics, the microcomb is attracting much interest. It's now a very hot research topic, due to strengths that include the compactness of the OFC, its efficiency, its ultra-wide band output, and its potential to serve in a wide range of applications. Microcombs could be used for spectroscopy, optical communication, metrology, optical atomic clocks, bio/chemical sensing, distance ranging and searching for exoplanets.

Progress with microcombs has propelled them to an advanced state called the octave and dissipative Kerr soliton, which realises self-reference and coherence. Thanks to the highly compact geometry, comb tooth spacings can now be in the range of tens of gigahertz to terahertz, further expanding the application range of traditional mode-locked laser combs.

Among the different material platforms that can be considered for photonic integration (see Table 2), SiC is one that is going to open a door to new optical devices, including microcombs, thanks to its unique optical properties. Its strengths include a wide bandgap, and high second-order and third order optical nonlinearity.

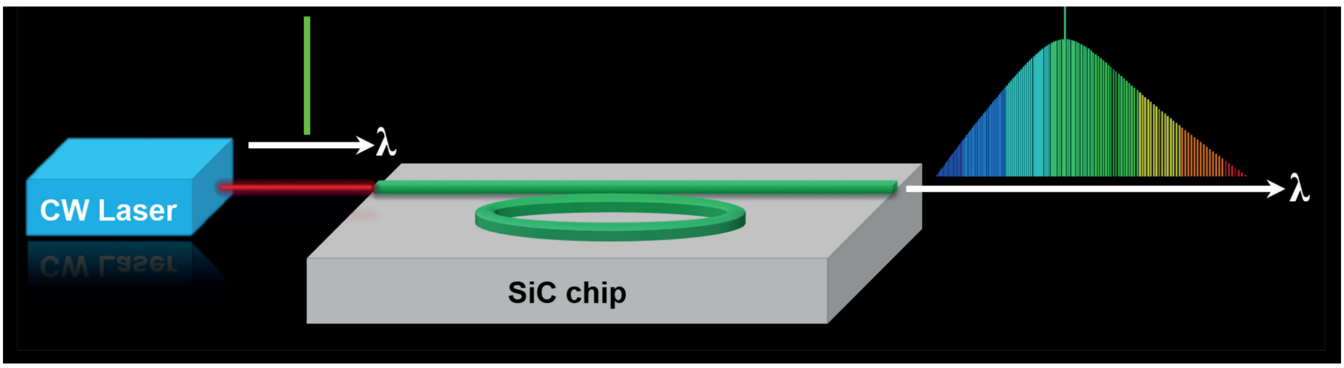
The chip-scale frequency comb, also called a microcomb, represents the third generation of OFC. It follows the mode-locked laser OFC, the first generation of this technology, and the more recent fibre laser OFC, the second generation of this technology

Due to its wide bandgap, frequency comb light sources based on SiC can cover an ultra-wide band from near ultraviolet to mid-infrared. Within this wide spectral domain disinfection, lighting, communication, biosensing and gas sensing all have individual footprints, some of which are yet to be covered by standard lasers. The high second-order and third-order non-linearity of SiC are advantageous, because they make the SiC frequency comb energy efficient and broad.

There are also significant opportunities for the SiC OFC in the likes of quantum optics and quantum networks, quantum computing, sensing, and imaging. This technology is sure to make an impact, enabling more secure and scalable integrated quantum networks, and possibly new embedded biosensors that revolutionise medical diagnosis, thanks to the biocompatibility of SiC material.

Over the last 10 years much progress has been made in chip-scale OFCs, also known as microcombs (see Figure 1 for a brief development roadmap since 2014). Key breakthroughs include the demonstration of chip-scale OFCs using MgF_2 in 2014, SiO_2 in 2015, Si_3N_4 in 2017, both AlGaAs and Hydex silica in 2018, $LiNbO_3$ in 2019, GaP in 2020, both Ta_2O_5 and SiC in 2021, and GaN in 2022.

Aside from $LiNbO_3$, which generates an OFC through second-order nonlinearity (an electro-optic



➤ Figure 2. SiCOI OFC generated from a microring resonator.

comb), the rest of the OFCs are realised through a third-order nonlinearity, and are known as a Kerr comb. Of these, Si_3N_4 is marked with an octave dissipative Kerr soliton, and provides a fully stable OFC. $LiNbO_3$, SiC, GaN and AlN are marked to have second-order nonlinearity. Unlike materials without second-order nonlinearity, these four have the capability to realise an octave bandwidth through wavelength conversion via frequency doubling. Despite the late arrival of SiC to OFCs, this material has caught up, demonstrating its capability and showcasing its tremendous potential in photonics, due to a nanofabrication-friendly nature and unique optical properties. Illustrating this point is a Kerr comb generated from a SiCOI microring resonator, shown in Figure 2.

Pioneering SiC OFCs

Our team is a trailblazer of SiC OFC technology, realising a number of important milestones over the last few years. In 2019 we reported the first integrated SiC microring resonator from 4H SiCOI made by the ion-cut method, as well as demonstrating four-wave mixing and deriving a non-linear refractive index for 4H SiCOI. A year later we demonstrated supercontinuum generation from 4H SiCOI waveguides made by the ion-cut method, and in 2021 we announced optical parametric oscillation from 4H SiCOI made by the ion-cut method. Further breakthroughs have followed in the last few years. In 2022 we demonstrated a 4H SiCOI beam splitter, polarisation beam splitter and Mach-Zehnder interferometer, and filed a patent for fabricating 4H SiCOI material stacks. And in 2023 we demonstrated: a 4H SiCOI polarisation and mode multiplexer; OFC from 4H SiCOI; and four-wave mixing from amorphous SiCOI, as well as deriving the non-linear refractive index for this particular material.

SiC is now attracting intensive interest for integrated photonics, spurred on by advances in crystal growth, thin-film transfer and nanofabrication. Key breakthroughs to date include the demonstration of second-order and third-order non-linearities in SiCOI. These non-linearities enable wavelength conversion, optical modulation/switching, optical frequency comb generation, and so on. Another important advance is the realisation of a family of high-performance passive components. Testing reveals that some of these components work in both the classic and quantum regime.

Leveraging the triumphs of SiC in integrated photonics, this material is making a promising entry into integrated quantum photonics. Here one of its attributes is the multi-species of colour centres, which could offer a solution in the quest for single-photon sources operating at room temperature.

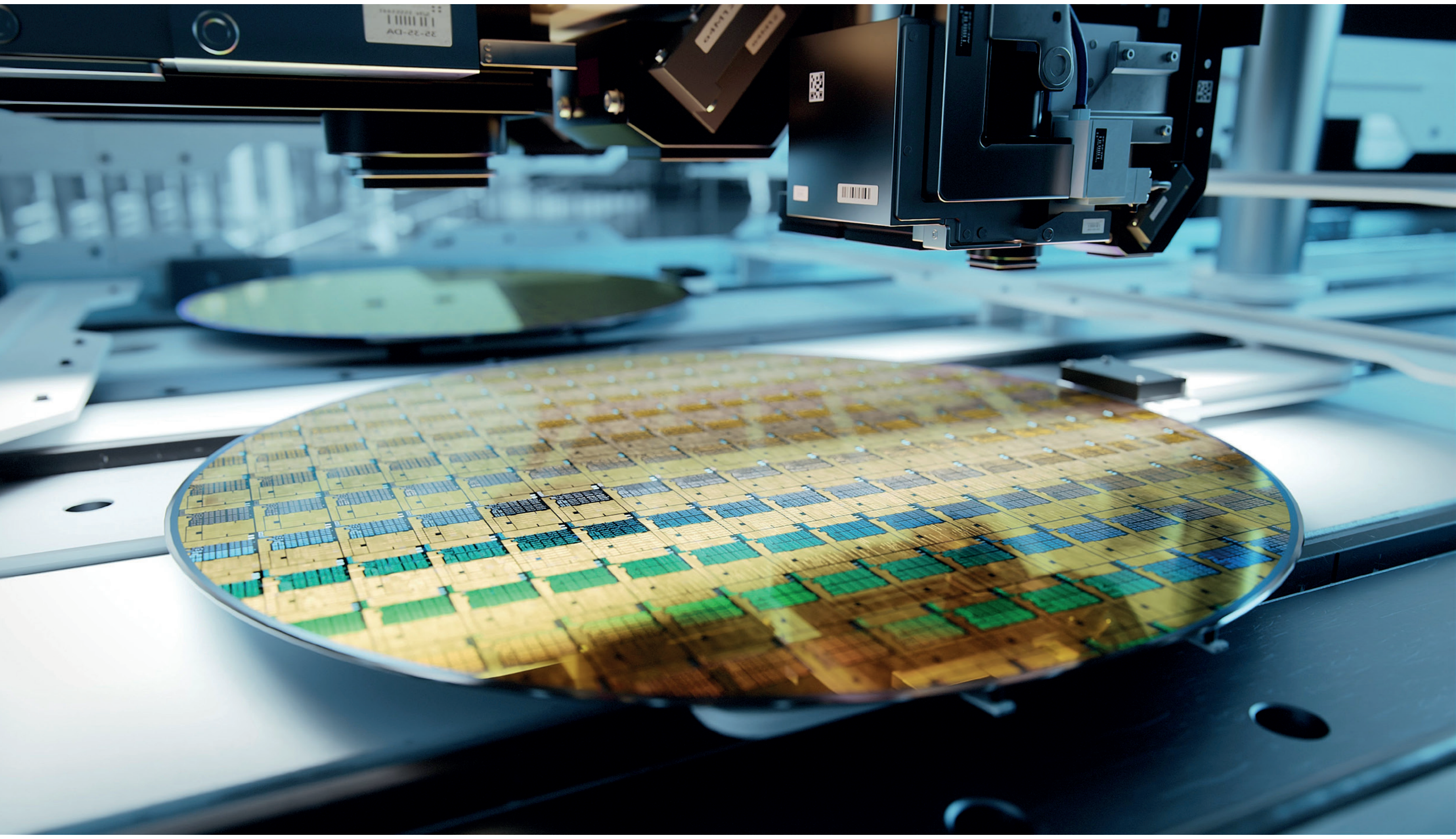
Looking ahead, in the short term our plans include developing and optimising the six building blocks for integrated photonics with SiCOI. In a long term, SiC will be an active player as a material platform for quantum photonic integrated circuits, with the monolithic integration of single-photon sources in SiCOI with other building blocks. SiCOI has the potential to outperform diamond, in terms of both scalability and its wide selection of colour centres, with emission wavelengths spanning the visible to infrared. This material also appears to have the upper hand over III-V quantum dots, because SiCOI promises to produce single-photon sources working at room temperature, key to transferring quantum technology from the lab to practical applications.

We have the fortune to pioneer the SiC photonics field. We look forward to embracing upcoming opportunities and challenges, to driving further development of this technology, and to providing novel solutions for a more sustainable future.

Acknowledgement: EU H2020 FET Open project 'CMOS compatible and ultra-broadband on-chip SiC frequency comb' (SiComb, project No. 899679).

FURTHER READING

- H. Ou *et al*. "Novel Photonic Applications of Silicon Carbide" Materials **16** 1014 (2023)
- F. La Via *et al*. "Emerging SiC Applications beyond Power Electronic Devices" Micromachines **14** 1200 (2023)
- X. Shi *et al* "High-performance silicon carbide polarization beam splitting based on the asymmetric directional coupler for mode conversion" Opt. Lett. **48** 616 (2023)
- X. Shi *et al*. "Compact low-birefringence polarization beam splitter using vertical-dual-slot waveguides in silicon carbide integrated platforms" Photonics Res. **10** A8-A13 (2022)
- X. Shi *et al*. "Thermal Behaviors and Optical Parametric Oscillation in 4H-Silicon Carbide Integrated Platforms", Advanced Photonics Research 2100068 (2021)
- S. Castelletto *et al*. "Silicon Carbide Photonics Bridging Quantum Technology" ACS Photonics **9** 1434 (2022)
- X. Shi *et al*. "Polarization and Spatial Mode Dependent Four-wave Mixing in a 4H-Silicon Carbide Microring Resonator" APL Photonics **6** 076106 (2021)
- Y. Zheng *et al*. "4H-SiC microring resonators for nonlinear integrated photonics" Opt. Lett. **44** 5784 (2019)
- Y. Zheng *et al*. "High-quality factor, high-confinement microring resonators in 4H-silicon carbide-on-insulator" Optics Express **27** 13053 (2019)
- J.Li. et al. ''Efficient Raman Lasing and Raman–Kerr Interaction in an Integrated Silicon Carbide Platform'', ACS Photonics **11** 795 (2024)
- X. Shi *et al*. "High-performance polarization-independent beam splitters and MZI in silicon carbide integrated platforms for single-photon manipulation" J. Light. Technol. **40** 7626 (2022)



Integrating high-speed germanium modulators with silicon photonics and fast electronics

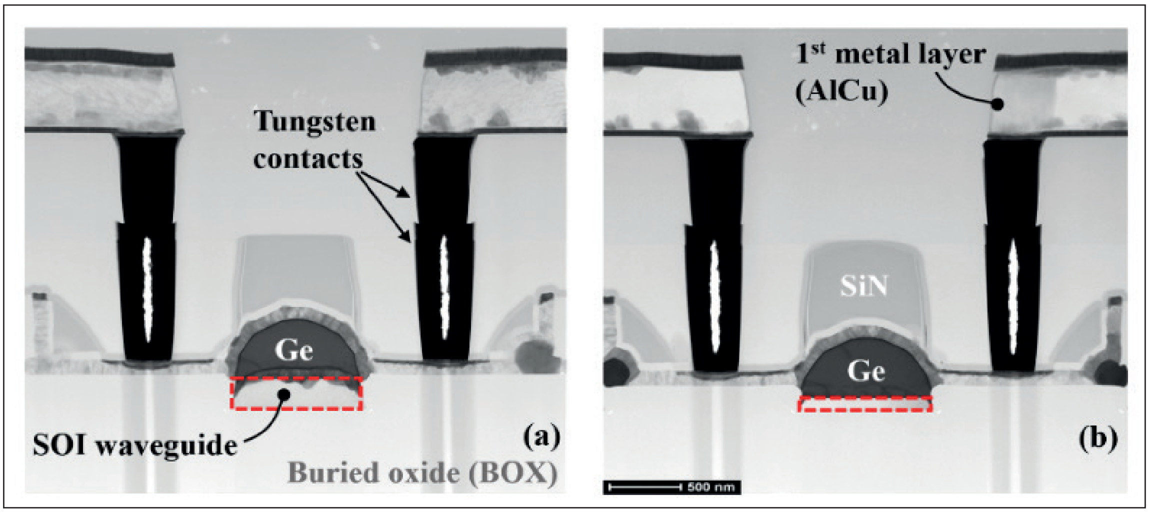
A major bottleneck in optical transmission is emerging, as silicon Mach-Zehnder modulators approach their limits. In our data-driven era, the industry urgently needs higher-bandwidth, energy-efficient modulators that are compatible with silicon photonics. Germanium electro-absorption modulators offer a promising route forwards.

BY DANIEL STECKLER, STEFAN LISCHKE, AND LARS ZIMMERMANN, IHP-LEIBNIZ INSTITUT FÜR INNOVATIVE MIKROELEKTRONIK

OPTICAL CONNECTIVITY plays a major role in all our daily lives, often without us even noticing it. Video calls, cloud storage, social media, and on-demand video and audio are all constantly at our fingertips. Artificial intelligence (AI) applications are also on the way to becoming ubiquitous everyday companions. But all of this is only possible thanks to modern datacentres. Fibre-optic communication, not only to and from datacentres, but also within them, is the key to coping with the enormous data flow these technologies generate.

According to the Ericsson Mobility Report from November 2023, global data traffic has more than doubled every two years over the past 10 years. By 2029, global mobile data traffic is projected to triple, reaching 403 exabytes per month [2]. Since every single bit transmitted consumes a certain amount of energy, the energy efficiency of optical and electrical devices is increasingly important. One hyperscale datacentre already consumes as much energy as 80,000 US households [1]. And that doesn't even include the energy required for transport to the datacentres.

Besides energy efficiency, other demands on future devices include high-volume and low-cost fabrication capabilities and high-speed performance.



➤ Figure 1: TEM images of germanium photodiode (a) and electro-absorption modulator (b). Cross sections cut perpendicular to the light-incidence direction. As indicated by the red boxes the Si-region has been reduced from 220 nm to 100 nm for the electro-absorption modulator.

Thanks to sophistic–ated fabrication processes on 200 mm and 300 mm wafers, silicon photonics has seen rapid progress, becoming a major technology in fibre-optic communication applications. In fact, silicon photonic transceivers for datacentre interconnects enabling 400 G bitrates are already available on the market and 800 G transceivers have been demonstrated.

However, while the effective data rates of transceivers have increased from 10 G in 2007 to 800 G in 2024, the rate of transmitted light pulses (symbol or baud rate) has actually only scaled by a factor of five (from 10 GBaud, in 2007 to 50 GBaud today). For this reason, techniques such as higher-order modulation or multiple lanes are deployed on a large scale to cope with the data-traffic requirements [3].

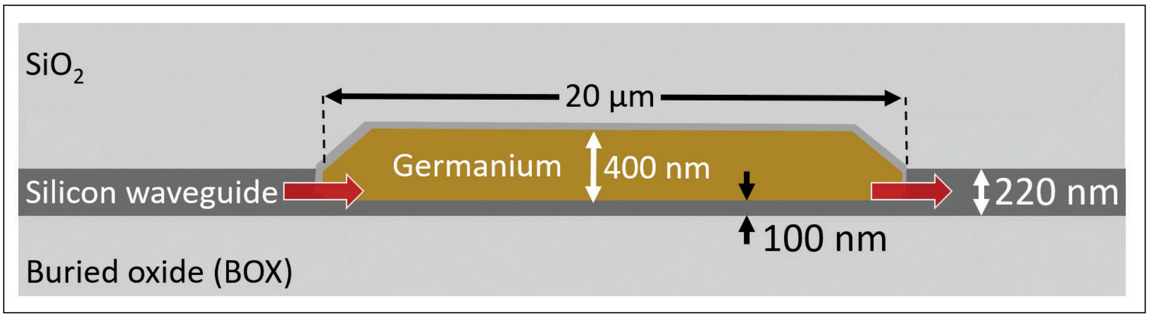
On the receiver side, germanium photodetectors with a 3 dB bandwidth well beyond 200 GHz have already been demonstrated [4]. However, a major bottleneck is emerging on the transmitter side. With electro-optical 3 dB bandwidths of 50-70 GHz, silicon Mach-Zehnder modulators, the most established devices in silicon photonic transmitters, seem to have reached their performance limits already. Facing the data-traffic growth projections, it is unlikely that using the aforementioned modulation formats or even more parallelisation alone will be sufficient. Achieving symbol rates beyond 100 GBaud will require extensive equalisation and digital signal processing (DSP), but this is detrimental to the system's power efficiency. To avoid this, the industry urgently needs modulators with 3 dB bandwidths above 100 GHz.

To this end, researchers have put extensive efforts into developing alternative modulators in recent years, investigating materials such as lithium niobate, barium titanate, silicon-organic hybrid modulators, and plasmonic modulators. In 2023, for example, researchers demonstrated resonant plasmonic micro-racetrack modulators with 3 dB bandwidths of 176 GHz and symbol rates of 220 GBaud [5].

However, monolithic integration of modulators based on "exotic" materials onto silicon photonics platforms presents considerable challenges, such as CMOS cleanroom compatibility, cross-contamination, and reliability. To date, no full platform integration of such modulators has been demonstrated without significant performance losses.

Electro-absorption modulators

To overcome the bandwidth bottleneck, we need a modulator that is compatible with silicon photonics, simultaneously enables bandwidths above 100 GHz,



➤ Figure 2: Schematic longitudinal cut through the EAM to visualize the butt-coupling approach (not to scale).

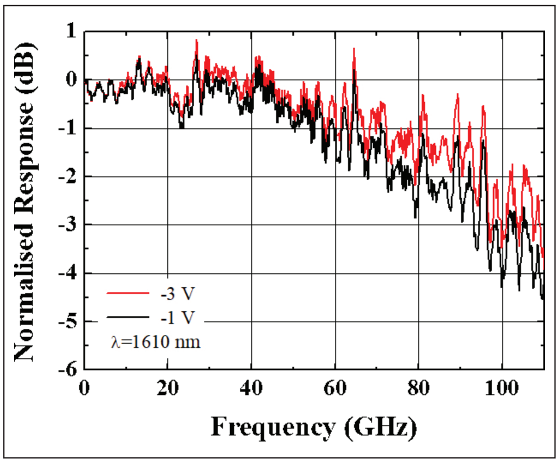


Figure 3: Normalized frequency response of electro-absorption modulator at wavelength of 1.6 µm at a bias of -1 V and -3 V for an optical input power of P_{in} = 6 dBm at fibre tip, estimated on Keysight 110 GHz LCA.

and also allows energy-efficient optical modulation. Germanium electro-absorption modulators (EAMs) represent a very promising candidate for meeting these criteria.

For this purpose, we can use a device with a structure very similar to a photodiode. While the latter is located at the end of an optical waveguide (where the incident light is converted into photocurrent), the modulator is intended to change the intensity of the light, by either absorbing or transmitting it. For transmission, the incoming light must not be absorbed, which limits the usable wavelengths to the range where germanium no longer absorbs. This happens in the range of 1.6 µm and beyond.

However, we can significantly enhance the optical absorption of germanium in this wavelength range with the application of an electric field – a phenomenon known as the Franz-Keldysh effect. In other words, we can use an electric field to change the optical absorption of a semiconductor – hence the term electro-absorption modulators (EAMs). The Franz-Keldysh effect is intrinsically a very fast process and theoretically enables modulation in the THz regime. However, the EAM itself is limited by the time it takes for the electric field to build up, which is governed by the resistance and capacitance of the device.

In 2007, MIT scientists demonstrated the first waveguide-coupled germanium EAM with a 3 dB bandwidth of around 1 GHz [6]. Since then, a lot of research has gone into increasing the performance of these devices. In 2023, the National Information Optoelectronics Innovation Center in Wuhan, China, demonstrated a germanium EAM with a 3 dB bandwidth higher than 110 GHz [7].

IHP's silicon-germanium BiCMOS technology

At IHP, we are aiming to develop and improve germanium EAMs with 3 dB bandwidth of at least 100 GHz to be further integrated into our unique photonic silicon-germanium BiCMOS technology platform [8], a process that enables electronic PICs (ePICs).

This innovation monolithically combines photonic devices such as optical waveguides, phase shifters and high-speed germanium photodiodes with CMOS transistors and high-performance silicon-germanium heterojunction-bipolar transistors (HBT) on the same wafer substrates. This benefits RF performance significantly while simultaneously reducing packaging and assembly efforts.

In 2023, we demonstrated the first >100 GHz germanium EAM monolithically integrated along with germanium photodiodes with 3 dB bandwidth of 80 GHz. Indeed, both of these devices were integrated into the aforementioned photonic BiCMOS technology platform, i.e. together with CMOS and silicon-germanium HBT [9].

IHP's germanium EAM device scheme is in general very similar to that of the photodetector. However, the requirements on the coupling between the silicon waveguide and the germanium are different, because absorption must happen for photodetection, whereas an EAM must perform amplitude modulation.

In the latter case, coupling is far more critical, since the optical mode should pass through the device with the lowest possible loss when the

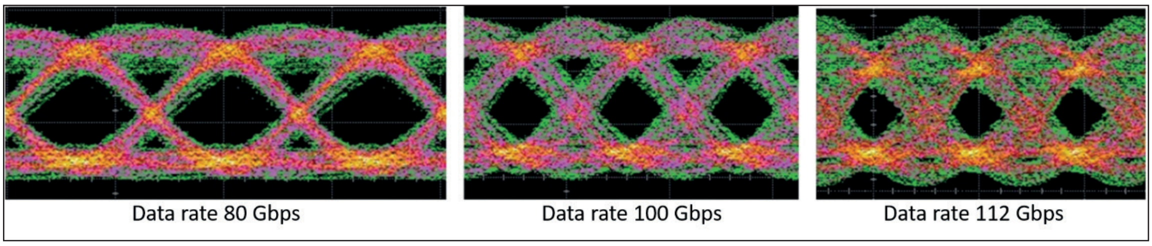


Figure 4: Eye diagrams of RF-probed germanium EAM at data rates of 80, 100, and 112 Gbps. The dynamic extinction ratios are 2.9 dB (80 Gbps), 2.75 dB (100 Gbps), and 2.3 dB (112 Gbps) with four-tap linear equalization on the receiver side. V_{bias} = -1.5 V and an AWG output signal of 2.3 V_{pp}.

device is in the off state (when it is supposed to be "transparent"). Therefore, it is essential to maximise the overlap between the optical modes of the silicon waveguide and the germanium region of the EAM. We can achieve this by locally reducing the silicon thickness below that of the germanium.

In our technique, we were able to realise this without additional processes or mask efforts, by utilising the silicon dry etch originally applied to form rib waveguides for silicon Mach-Zehnder modulator phase shifters.

Figure 1 shows cross sections of the germanium photodiode and EAM, obtained by tunnelling electron microscopy. Figure 2 shows a schematic longitudinal cut through the EAM. With a length of only 20 µm, these are very compact devices compared with silicon Mach-Zehnder modulators, which are typically several millimetres long.

High-speed results

Our germanium EAMs exhibit excellent RF performance with a 3 dB bandwidth of 100 GHz at -3 V bias. These devices' high-speed performance yields clearly opened eye diagrams at a data rate of 112 G. Figures 3 and 4 show the frequency response of the EAM and the eye diagrams, respectively.

The dynamic power consumption can be calculated by $\Delta E_{bit} = CV_{pp}^2/4$, where C is the junction capacitance and V_{pp} is the modulation voltage. With C = 7.5 femtofarad and V_{pp} = 1.8 V, the dynamic power consumption is estimated to be 6.08 femtojoules per bit, which is a peak value amongst the silicon photonics-based modulators published to date.

In our technique, we were able to realise this without additional processes or mask efforts, by utilising the silicon dry etch originally applied to form rib waveguides for silicon Mach-Zehnder modulator phase shifters

In particular, the Franz-Keldysh effect enables efficient absorption in the wavelength range in which germanium otherwise absorbs only poorly. At λ = 1.6 µm, the co-integrated germanium photodiodes yield reasonably high internal responsivities of 0.33 A/W at -2 V and 0.45 A/W at -4 V bias. Simultaneously, the photodiodes exhibit 3 dB bandwidth of 80 GHz, determined at the same wavelength, as shown in Figure 5. Thus, the photodiode complements the fast modulators, which is crucial for monolithic integrated transceiver systems.

	imec	Intel	imec	CEA-Leti	AMF	IHP, this work
Platform	PIC	PIC	PIC	PIC	PIC	EPIC
Modulator type	EAM	RRM	RRM	MZM	MZM	EAM
Resonant device	No	Yes	Yes	No	No	No
EO bandwidth (GHz)	>50	62	45	40	>40	100
Symbol rate (Gbd)	56	128	-	-	56	112
Equalization techniques	n/a	21-tap Tx FFE 32-tap Rx FFE	-	-	No equalization	4-tap Rx FFE
Dynamic Extinction Ratio (dB)	3.3 (2 V_{pp})	3.4 (1.8 V_{pp})	-	-	3.9 (3 V_{pp})	2.3 (1.8 V_{pp})
Insertion Loss (dB)	4.9	6	-	2.4	4	7-8.5
Device Length or Radius (µm)	40	4	5	3000	4000	20
Calculated dynamic power consumption of EAM (fJ/bit)	13.8	20.25	25	~200 (estimated)		6.08
Operational window	C-, L-band	O-, C-, L-band	O-, C-, L-band	O-, C-, L-band	O-, C-, L-band	L-Band

➤ Table 1: Overview of state-of the art Si-based modulators available in recent silicon photonics platforms. We compare Mach-Zehnder modulators (MZM) to resonant ring modulators (RRM) and electro-absorption modulators (EAM) as more compact device alternatives. Definition of the optical windows: O-band: 1260-1360 nm, C-band: 1530-1565 nm, L-band: 1565-1625 nm.

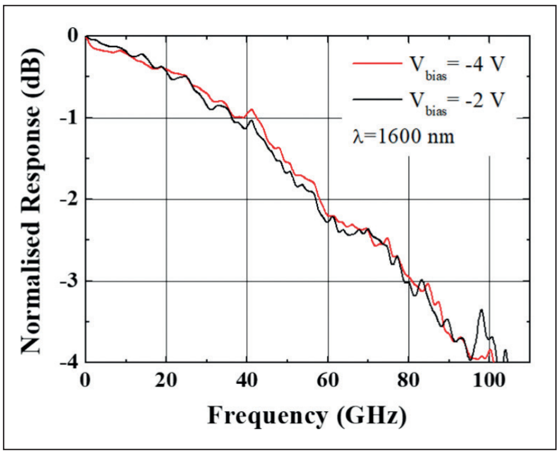


Figure 5: Normalized frequency response of germanium photodiode at a wavelength of 1.6 μm for optical input power of P_{in} = 0 dBm at fibre tip, estimated on Keysight 110-GHz lightwave component analyzer (LCA).

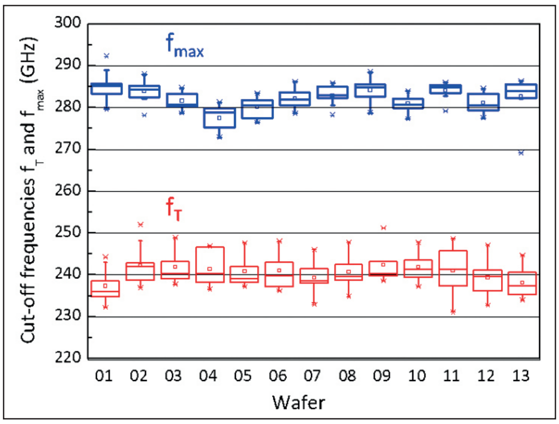


Figure 6: Box-plots of unity gain frequency f_T and of maximum oscillation frequency f_{max} measured on 13 wafers from one lot, 9 chips measured on each wafer.

Importantly, integrating EAMs did not reduce the performance and yield of the electronic components such as 0.25 µm CMOS transistors and silicon-germanium HBTs. Figure 6 demonstrates the high-frequency behaviour of the latter, showing cut-off frequencies f_T and f_{max} of ~240 GHz and ~280 GHz, enabling high-speed modulator driver or transimpedance amplifier circuits.

Table 1 compares various silicon photonics platforms by means of their modulator performance to benchmark our results. In comparison with the other modulators, our ePIC-integrated EAM exhibits outstanding performance in terms of energy efficiency and electro-optical bandwidth.

These characteristics will pave the way for the design of small-footprint transmitters for >100 GBaud data-rate applications to cope with future data-traffic requirements.

Outlook

To date, our EAM has demonstrated promising results at wavelengths within the L-band (around 1610 nm). For a broader range of applications, however, operation within the C-band (1530-1565 nm) is favoured due to its widespread use in telecommunications.

This can be addressed by fine-tuning the absorption characteristics through the incorporation of silicon into the germanium. Researchers at MIT and imec have previously demonstrated that a silicon content in the range of about 1 percent shifts the absorption into the desired wavelength region.

We aim to further identify and overcome current bandwidth limitations in order to optimise the germanium EAMs towards 3 dB bandwidths well beyond 100 GHz, pushing the boundaries of what is currently achievable.

FURTHER READING / REFERENCE

- [1] https://blog.enconnex.com/data-cente energy-consumption-and-power-sources
- [2] https://www.comcom.admin.ch/comcom/en/Homepage/documentation/facts-and-figures/mobile-telephony/mobile-data-traffic.html
- [3] X. Zhou et al., "Beyond 1 Tb/s Intra-Data Center Interconnect Technology: IM-DD OR Coherent," in Journal of Lightwave Technology, vol. 38, no. 2, pp. 475-484, 15 Jan.15, 2020
- [4] Lischke, S., Peczek, A., Morgan, J.S. et al. Ultra-fast germanium photodiode with 3-dB bandwidth of 265 GHz. Nat. Photon. 15, 925–931 (2021). https://doi.org/10.1038/s41566-021-00893-w
- [5] M. Eppenberger et al. "Resonant plasmonic micro-racetrack modulators with high bandwidth and high temperature tolerance," Nat. Photon. 17, 360-367 (2023)
- [6] J. Liu et al. "Design of monolithically integrated GeSi electro-absorption modulators and photodetectors on an SOI platform," Opt. Express 15, 623-628 (2007)
- [7] X. Hu et al. „280 Gbit/s PAM-4 Ge/Si Electro-absorption Modulator with 3-dB Bandwidth beyond 110 GHz," Optical Fibre Communications Conf. and Exhibition (2023)
- [8] S. Lischke, D. Knoll, C. Mai, and L. Zimmermann, "Advanced photonic BiCMOS technology with high-performance Ge photo detectors," Proc. SPIE, vol. 11088, pp. 46–56, Sep. 2019, doi:10.1117/12.2530143.
- [9] D. Steckler et al. , "Monolithic Integration of 80-GHz Ge Photodetectors and 100-GHz Ge Electro-Absorption Modulators in a Photonic BiCMOS Technology," in IEEE Transactions on Electron Devices, vol. 71, no. 5, pp. 3417-3423, May 2024


VPIphotonics
DESIGN AUTOMATION
PROFESSIONAL SIMULATION TOOLS & EXPERT DESIGN SERVICES
Integrated Devices, Waveguides & Fibers
VPIdeviceDesigner™
Photonic Integrated Circuits
VPIcomponentMaker™ Photonic Circuits
Fiber Amplifiers & Lasers
VPIcomponentMaker™ Fiber Optics
Transmission Systems
VPItransmissionMaker™ Optical Systems
Lab-proven DSP Algorithms
VPItoolkit™ DSP Library
Quantum Key Distribution
VPItoolkit™ QKD
We empower you to
define the cutting edge.
Request an evaluation
www.VPIphotonics.com

Designing for manufacture:

PAM-4 transmitters using segmented-electrode Mach-Zehnder modulators

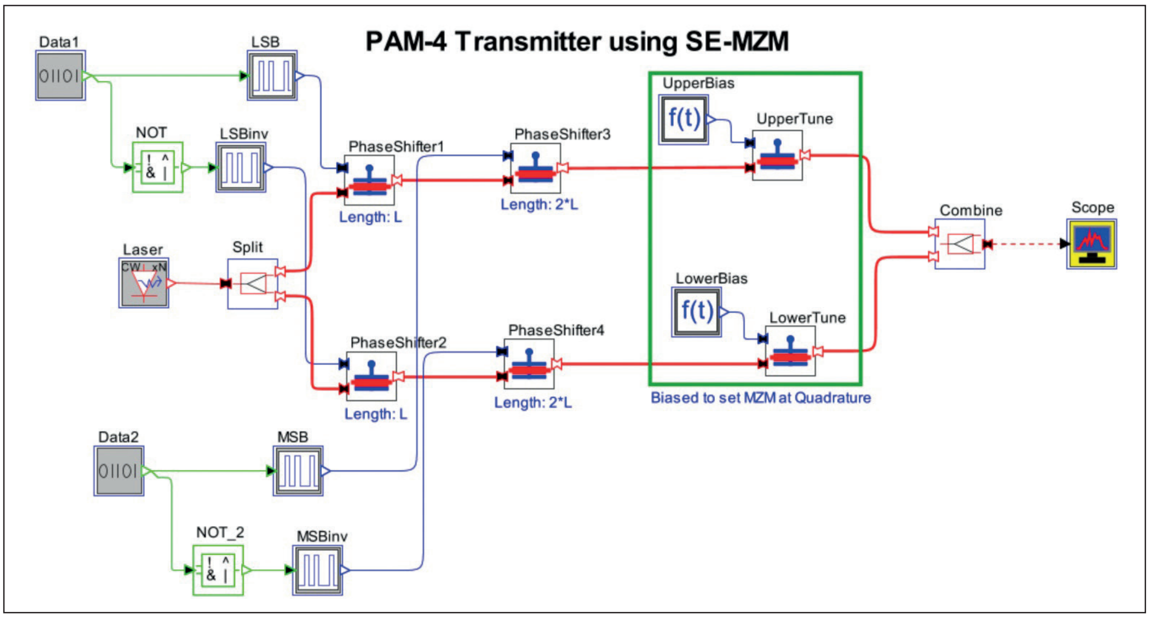
As PAM-4 signalling becomes the norm in datacentre optics, there is increasing focus on finding optimal design and implementation of the PAM-4 transmitter PICs. We use Synopsys' OptSim software to simulate a design using segmented-electrode Mach-Zehnder modulators and investigate how manufacturing variations affect its performance.

BY JIGESH PATEL, PRODUCT MANAGER, AND PABLO MENA, R&D ENGINEER, SYNOPSYS

IN DATACENTRE OPTICS, 4-level Pulse Amplitude Modulation (PAM-4) signalling is gradually overtaking non-return-to-zero (NRZ) signalling [1-3]. Although both schemes use intensity modulation and direct detection, PAM-4 encodes two bits into four intensity levels, reducing bandwidth requirements for a given data rate by half. In other words, with PAM-4, transmission of a 40G signal requires components with 20 GHz bandwidth (corresponding to a symbol rate of 20 GBaud).

PAM-4 strikes a good balance between data carrying capacity and cost, since it requires less complicated digital signal processing than coherent transmission methods. Since lowering energy consumption is an economic and social imperative, designers need to be mindful of energy efficiencies when exploring technologies. This article explores the design of a PAM-4 transmitter chip that provides higher bandwidth compared to NRZ, avoids using energy-inefficient electronics, and achieves PAM-4 signalling in the optical domain by using segmented-electrode phase-shifters.

Commonly used PAM-4 transmitter PICs often suffer from poor energy efficiency and larger footprint. Traditionally, these transmitters incorporate a Mach-Zehnder modulator (MZM) being driven by an



➤ Figure 1. Schematic of a PAM-4 transmitter using SE-MZM

electrical digital-to-analogue converter (DAC) with an electrical driver. But the electronics required for this is highly energy inefficient – an ever-increasing concern in datacoms. Although there are alternative designs with nested modulators and drivers, a drawback is that they typically have larger footprints.

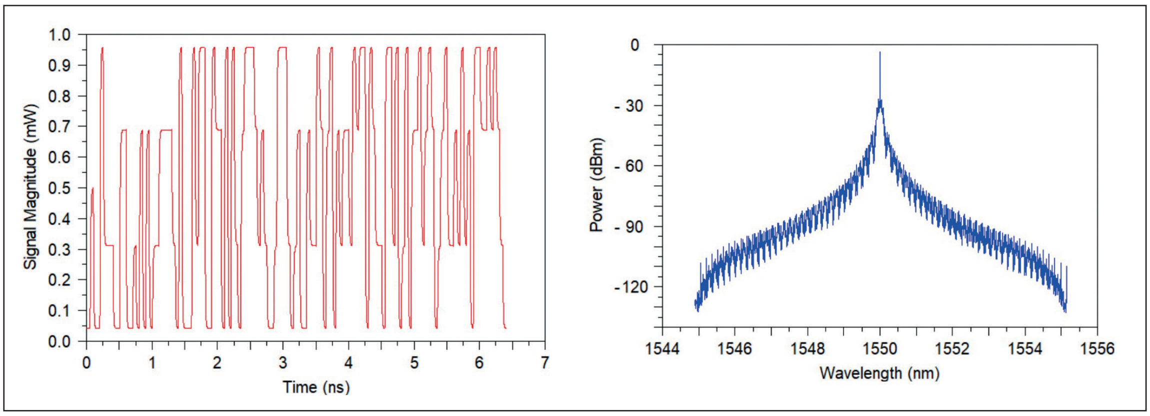
To overcome these challenges, we can accomplish a DAC-less design using the inherent DAC capabilities of segmented phase shifters [4]. Although conventional travelling-wave MZMs (TW-MZMs) can reduce drive voltage ($V_{\pi}L$) due to a longer interaction length (L) thereby improving energy efficiency, the longer electrodes result in higher radio frequency (RF) losses and a mismatch between the group velocities of RF and optical signals. This mismatch, in turn, impacts modulation bandwidth [5].

The segmented approach offers the advantage of longer interaction lengths without increasing loss, by shifting the velocity matching to electronic timing circuits, which control the timing of applied electrical signals to match the optical delay between segments [6]. Figure 1 shows a schematic of a PAM-4 transmitter using an SE-MZM made from discrete PIC elements. The design is built in Synopsys OptSim – an advanced photonic circuit simulation tool, which is part of the Synopsys electronic-photonic design automation (EPDA) toolset.

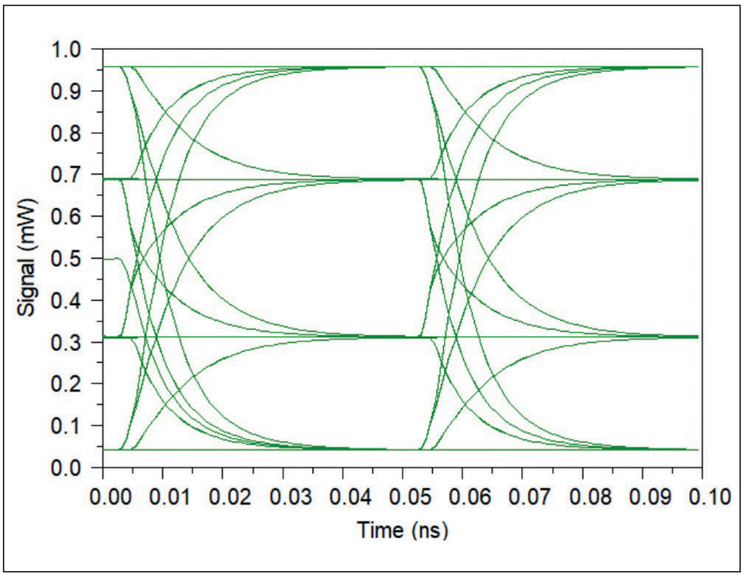
The topology comprises bidirectional PIC elements such as a 1-input 2-output optical splitter and a 2-input 1-output optical combiner with user-defined power ratio, and two pairs of travelling-wave optical phase shifters. The latter are used to implement the segmented MZM. Their lengths are binary weighted, meaning that each binary word can be applied directly. This minimises the number of segments needed, making integration less complicated.

The first segment's length is one third of the total MZM length, while the second segment is two thirds of the total length. The 20G bit sequence has already been split into separate bit patterns corresponding to the most and least significant bits (MSB and LSB, respectively). The top driver modulates the first MZM segment using the LSB pattern, and the bottom driver modulates the second MZM segment using the MSB pattern.

Each travelling-wave phase shifter has an optical waveguide and a surrounding electrical transmission line that can change the waveguide's refractive



➤ Figure 2. SE-MZM PAM-4 transmitter output signal (left) and spectrum (right).



➤ Figure 3. Optical eye diagram at the transmitter output.

index and propagation loss. The interaction between the electrical and optical signals is distributed along the propagation direction. The waveguide's thermal behaviour – and hence also the thermal behaviour of the modulator – can be modelled with the derivative of effective refractive index, the parameter $V_{\pi}L$, and propagation loss as functions of temperature [7].

Each MZM arm also has a phase tuner near the combiner, which sets the modulator at quadrature. A simple 90-degree phase-shifter model from OptSim in one of the arms could have performed the same job. However, for a packaged product, external controls allow for any additional tuning that might be needed, for example due to environmental factors or manufacturing tolerances.

The continuous-wave (CW) light is modulated by an electrical signal derived from pseudorandom binary signal (PRBS) data followed by an electrical driver. The inverter model provides a push-pull electrical bias to one of the electrodes relative to the other. A scope placed at the output of the SE-MZM PIC observes the PAM-4 modulated optical signal and its spectrum, depicted in Figure 2. Meanwhile, Figure 3 shows the four-level PAM-4 optical eye diagram at the transmitter's output.

Impact of inter-segment distance deviations

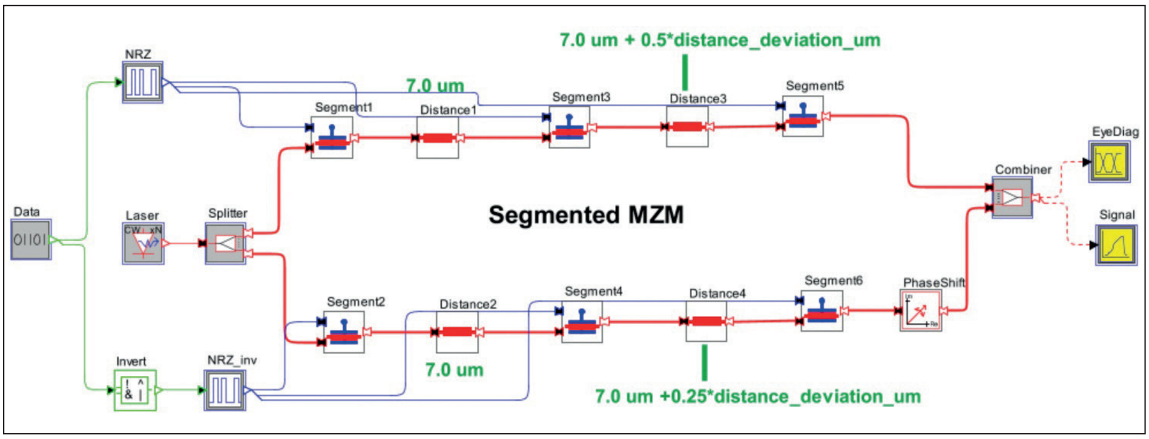
While this segmented design concept offers a promising way forward for energy-efficient, small-footprint PAM-4 transmitters, several factors could impact the transmission signal quality. It's particularly important to understand how deviations from the design introduced by the manufacturing processes can affect functionality.

For simplicity, we use an SE-MZM PAM-2 transmitter in OptSim, although the discussion also applies to higher-level PAM signals, including PAM-4. We analyse how performance varies with deviations in key parameters such as segment-to-segment distance, driver time-delay, and response time. All of these parameters can be affected by manufacturing and packaging process variations and have a direct impact on the overall yield of SE-MZM-based high-speed transmitter PICs.

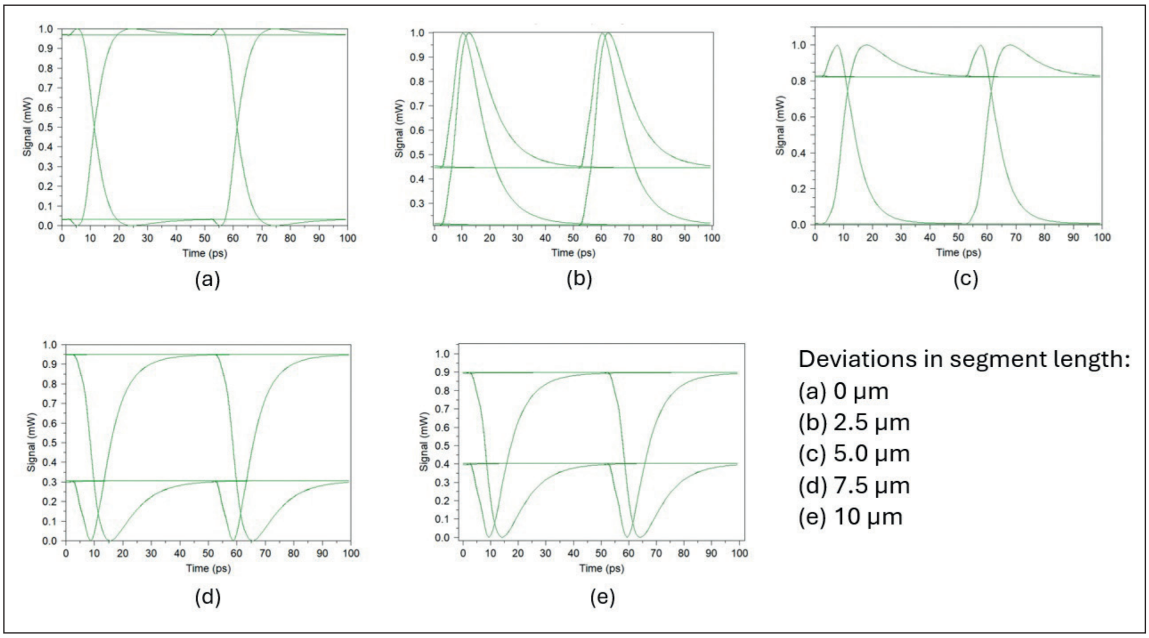
In SE-MZMs, electrodes are split in segments of specific lengths to achieve the desired level of amplitude modulation. Whether the phase shifter lengths are binary weighted or thermometer coded [8], variations in the manufacturing process can result in deviations in the inter-electrodes, thereby affecting the MZM's bias and bandwidth. OptSim is an excellent platform with which to conduct Monte Carlo analyses and achieve design for manufacturing [9].

Figure 4 shows a PAM-2 transmitter using an SE-MZM made from discrete PIC elements in OptSim. Similarly to the PAM-4 transmitter design discussed earlier, the topology comprises bidirectional PIC elements such as a 1-input 2-output optical splitter and 2-input 1-output optical combiner with user-defined power ratio, and pairs of travelling-wave optical phase shifters.

OptSim's bidirectional waveguide model connects the phase shifters and implements deviations in the separation between the segmented electrodes. By setting a parameter scan for distances between the electrode segments, we can obtain the PAM-2 modulated optical eye diagrams shown in Figure 5. The bandwidth narrowing due to deviations in



➤ Figure 4. Schematic of a PAM-2 transmitter using SE-MZM.



➤ Figure 5. Optical eye diagrams at the transmitter output.

inter-electrode distances is clear: the higher the deviation, the worse the eye opening.

Impact of driver time-delay deviations

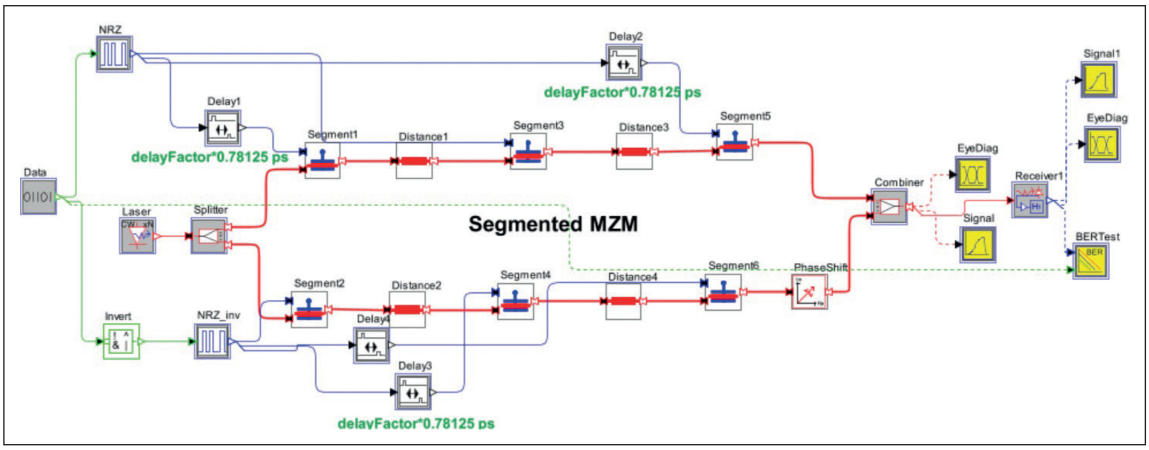
In SE-MZM transmitters, phase shifters are driven by electrical driving circuits. There are several manufacturing process variations and packaging constraints that can affect the device's properties. For example, slight variations in the chip placement in a die can lead to differing lengths of the copper traces to electrical pads. These variations can result in electrical timing deviations in driving electrodes, thereby affecting the mismatch between RF and optical group velocities, and ultimately the bandwidth of the transmitter PIC.

We can study the impact of these driver time-delay deviations using a design for an SE-MZM PAM-2 transmitter similar to the one in the previous section. The OptSim schematic is shown in Figure 6. OptSim's bidirectional waveguide model connects phase shifters and implements separations between the segmented electrodes.

The electrical time delay component models driver timing delay deviations as integer multiples of the sampling interval. For the design under study, this is 0.78125 picoseconds, corresponding to a data rate of 20 GBaud sampled at 64 samples per symbol. The lower arm of the MZM uses a discrete 90-degree phase-shifter model from OptSim to bias the MZM at quadrature.

As with the schematic in Figure 1, the CW light is modulated by an electrical signal derived from PRBS data followed by an electrical driver, and the inverter model provides a push-pull electrical bias to one of the electrodes relative to the other. At the output of the SE-MZM PIC, an eye diagram analyser and a signal analyser are connected to observe the transmitter signal. A back-to-back receiver at the SE-MZM PIC's output detects the received signal, and the bit error rate (BER) tester is used to estimate the penalties induced on the BER due to driver time delay.

A parameter scan is set for driving delays at segment electrodes as integer multiples of the sampling interval. Figure 7 shows the PAM-2 modulated optical eye diagrams obtained for



➤ Figure 6. Schematic of a PAM-2 transmitter using SE-MZM.

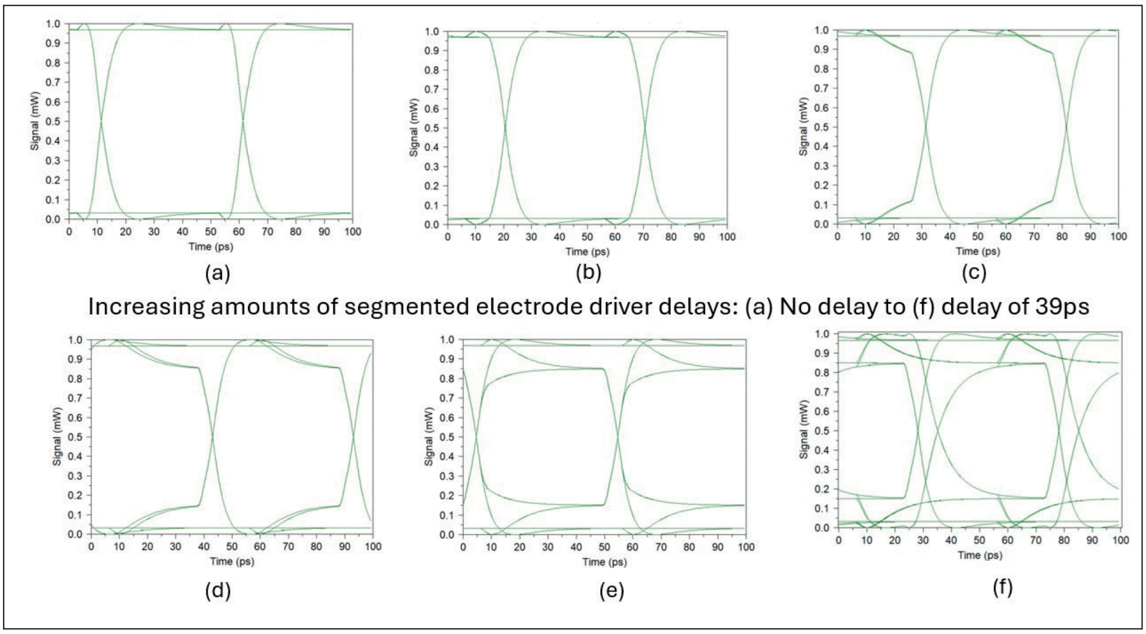


Figure 7. Optical eye diagrams at the transmitter output.

different values of drive delays. The resulting bandwidth penalties can also be visualised as back-to-back BER at the transmitter chip as shown in Figure 8. Optimal performance is achieved when the optical and RF group velocities match. This analysis can help designers find the optimal trace lengths to obtain performance within acceptable bounds.

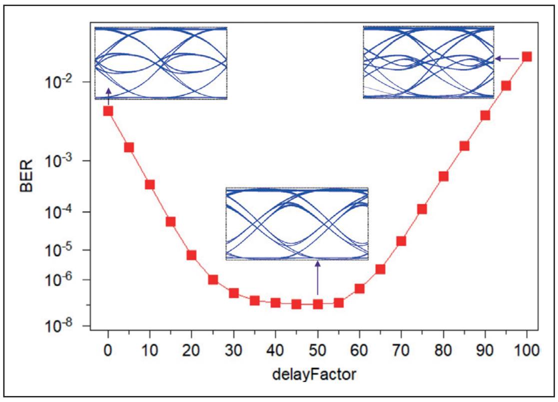


Figure 8. Bit error rate (BER) as a function of driving time delay.

Capacitive charge and R-C response times

Another important design consideration in SE-MZMs is the R-C response time of phase-shifter electrodes, which directly impacts the bandwidth of the transmitter PIC. The junction capacitance of the p-n diode and parasitics from packaging both contribute to the capacitive charge and R-C time limitations in a phase shifter. As shown in the schematic in Figure 9, we lump both effects into the overall R-C response time of the phase shifter.

After setting the electrical response model of the phase shifter to "RC," as shown in Figure 10, a parameter scan can be set for capacitance to model different amounts of capacitive charge and R-C response times. Figure 11 shows the PAM-2 modulated optical eye diagrams resulting from different values of R-C response times. As expected, higher response times adversely affect modulation speed.

Despite the three challenges outlined above, SE-MZM-based DAC-less transmitter PICs are nonetheless preferable in many contexts, due to their small footprint and high energy efficiency. However, to fulfil their potential, it is essential to consider the impacts of deviations in some of the

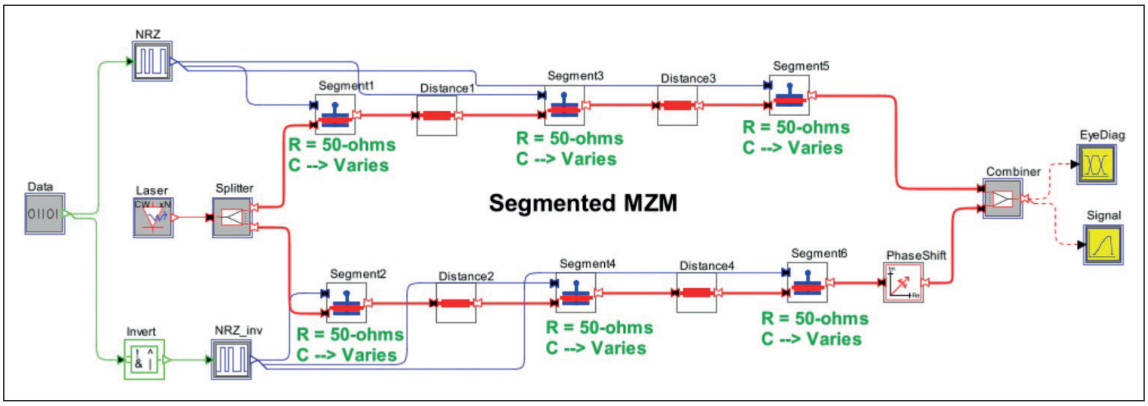
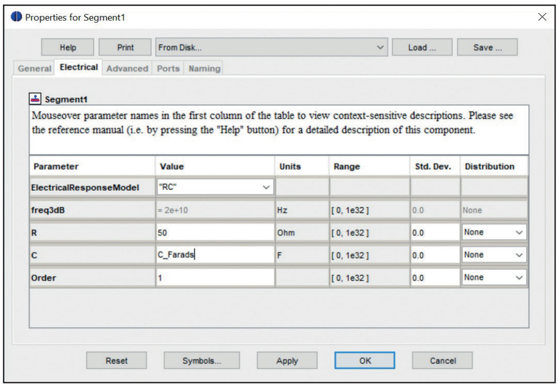
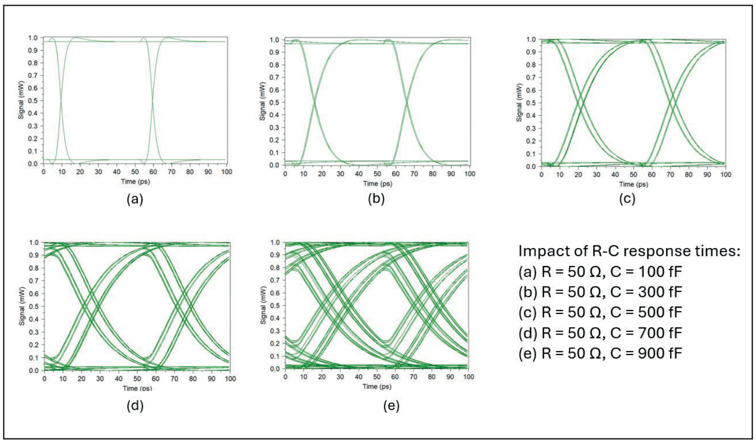


Figure 9. OptSim schematic of a PAM-2 transmitter using SE-MZM.



➤ Figure 10. Choice of electrical response model via the parameter window of the phase shifter model.



➤ Figure 11. Optical eye diagrams at the transmitter output.

key design parameters arising from packaging, technology, and manufacturing process variations. OptSim is a powerful tool for understanding these effects and thus achieving design for manufacturing and creating high-performance, reliable products.

Although this article has described optical performance in terms of eye diagrams at the transmitter, it is also possible to measure it in terms of performance penalty. Two of the most common performance metrics in NRZ transmitter design are extinction ratio and the dispersion penalty at maximum dispersion. In the case of PAM-4 transmitters, the equivalent quantities are optical modulation amplitude (OMA) and dispersion eye closure penalty quaternary (TDECQ) [10].

For the specified value of symbol error rate (SER), the TDECQ algorithm seeks to determine the maximum amount of noise that can be added to the input signal while still meeting the target SER, and then compare this to the amount of noise that could be added if the signal were ideal.

The TDECQ measurement functionality in Synopsys OptSim also produces plots of several quantities of interest, in addition to the TDECQ, to help with a detailed assessment of the transmitter compliance and equaliser performance. These additional transmitter performance parameters include optimised decision shift, reference-equaliser noise enhancement, OMA, and noise characteristics of the incoming and ideal signals. A detailed discussion of TDECQ measures is beyond the scope of this article, but more information is available in reference [11].

FURTHER READING / REFERENCE

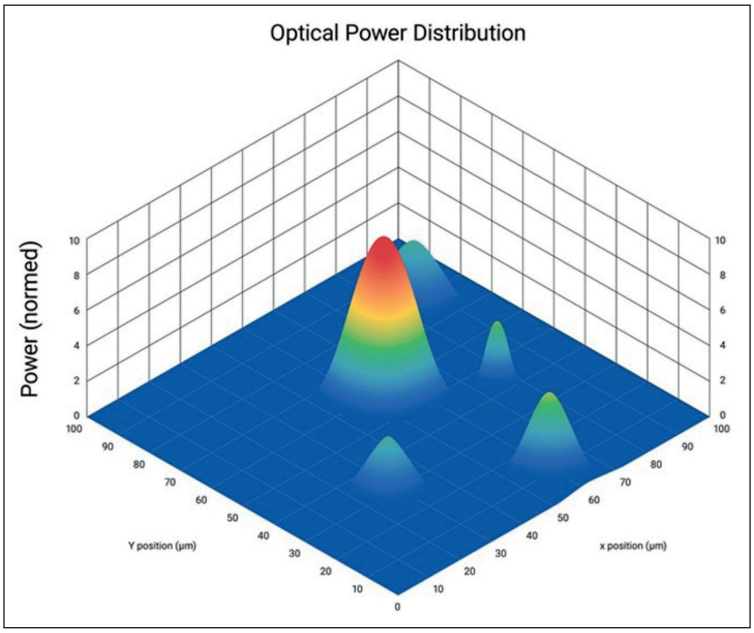
- [1]. Radhakrishnan Nagarajan, Mark Filer, Yang Fu, Masaki Kato, Todd Rope, James Stewart, “Silicon photonics-based 100 Gbit/s, PAM4, DWDM data canter interconnects,” Journal of Optical Communication Networks, vol. 10, no. 7, July 2018, pg. B25-B36
- [2]. Pablo V. Mena, Enrico Ghillino, Ali Ghiasi, Brian Welch, Muhammad Khaliq, Dwight Richards, “100-Gb/s PAM4 link modeling incorporating MPI,” DOI: 10.1109/OIC.2015.7115664, Proc. of 2015 IEEE Optical Interconnects Conference (OI), April 20-22, 2015, pg. 14-15
- [3]. Xiaotie Wu, Bipin Dama, et al., “A 20Gb/s NRZ/PAM-4 transmitter in 40nm CMOS driving a Si-Photonic modulator in 0.13µm CMOS,” 2013 IEEE International Solid-State Circuits Conference, Session 7, Doc. # 978-1-4673-4516-3/13, February 2013, pp. 128-131
- [4]. M. Papuchon, C. Puech, A. Schnapper, “4-bits digitally driven integrated amplitude modulator for data processing,” Electronics Letters, vol. 16, no. 4, Feb. 1980, pp.142-144
- [5]. https://www.novuslight.com/silicon-photonic-foundry-processes-and-traveling-wave-mach-zehnder-modulators_N4838.html
- [6]. Iria Garcia Lopez, et al., “DAC-free ultralow-power dual-polarization 64-QAM transmission at 32GBd with hybrid InP IQ SEMZM and BiCMOS drivers module,” Journal of Lightwave Technology, vol. 35, no. 3, Feb. 2017, pp. 404-410
- [7]. Hongtao Lin, Okechukwu Ogbuu, Jifeng Liu, Lin Zhang, Jurgen Michel, and Juejun Hu, “Breaking the energy-bandwidth limit of electrooptic modulators: Theory and a device proposal,” Journal of Lightwave Technology, vol. 31, no. 24, December 15, 2013, pg. 4029-40
- [8]. Michael Vanhoecke, at al., “Segmented optical transmitter comprising a CMOS driver array and an InP IQ-MZM for advanced modulation formats,” Journal of Lightwave Technology, vol. 35, no. 4, Feb. 2017, pp. 862-867
- [9]. https://www.synopsys.com/photonic-solutions/e-news/2018-november.html
- [10]. Jonathan King, “TDEC for PAM4 (TDECQ) – Changes to clause 123, to replace TDP with TDECQ, rev 1a,” TDEC for PAM4 (‘TDECQ’) (ieee.org), May 26, 2016
- [11]. Jigesh K. Patel, Pablo V. Mena, “TDECQ Compliance Testing of High-Speed PAM4 Transmitters in Synopsys OptoCompiler and OptSim,” https://www.synopsys.com/content/dam/synopsys/photonic-solutions/documents/whitepapers/tdecq-wp.pdf

Advances in active alignment engines for efficient photonics device test and assembly

The photonics market is advancing rapidly, with projected substantial growth in a large number of sectors incorporating this technology in the next decade. Anticipating devices with hundreds or even thousands of individual components and connections, manufacturers face the necessity of parallel optimization, making active alignment an optimal choice to meet production demands.

BY SCOTT JORDAN, STEFAN VORNDRAN AND WARREN HARVARD, PHYSIK INSTRUMENTE L.P. (PI)

OVER MORE than a half century, the pace of innovation in electronic communication and computing has consistently increased, giving rise to progressively smaller silicon microchips with enhanced processing power. This achievement is attributed to the exponential growth in the density of integrated circuit (IC) transistors, a development predicted by Gordon Moore, Intel confounder, in 1965 and commonly called Moore's Law. However, there are inherent limits to reducing the physical feature size of silicon structures before quantum effects start influencing their functionality.



➤ Optical power distribution of a photonic component and simulated hill-climb algorithm (gradient search). (Image courtesy PI).

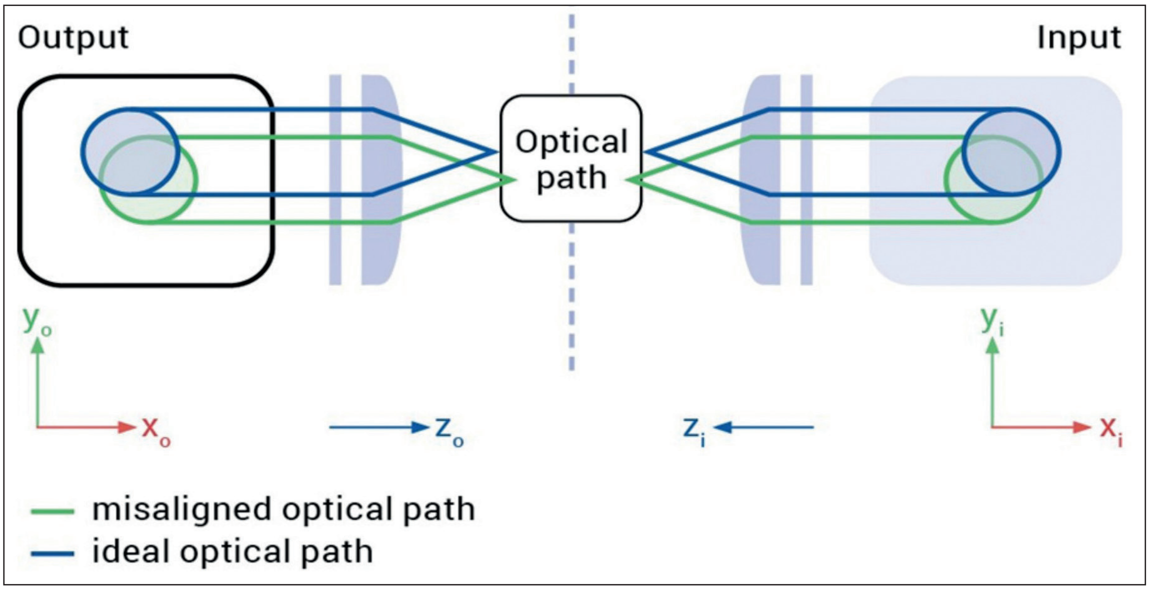
Fortunately, photonics has come to the aid of electronics, enabling the integration of miniaturized optical devices into various applications, from sensors in wearable devices, to LiDAR and ADAS cameras in autonomous vehicles. Photonics has the potential to surpass traditional electronics combining data throughput and efficiency with miniaturization, sparking a true revolution in the telecommunications and data communication sector. To sustain this growth, it is essential to address the remaining challenges and bottlenecks in photonic device manufacturing. The implementation of additional automation solutions, especially those ensuring fast and precise component alignment, is crucial to meet the demands of future advancements.

Limitations of labor-intensive device assembly

The assembly process of photonic devices typically includes meticulously aligning, gluing, and curing a combination of light sources, fibers, lenses, arrays, waveguides and chips. Each of these individual components must be accurately positioned to ensure the intended functionality and performance of the final product, as even slight misalignments on the orders of less than a millionth of a meter can severely impact device efficiency.

Despite technological advancements, many manufacturers still rely on manual alignment techniques, using shims for error compensation or securing hardware with retaining rings. Beyond being time-consuming, these methods often involve specialized labor that is both costly and challenging to find.

The manual assembly of complex devices can take up to 20 minutes, creating a significant bottleneck

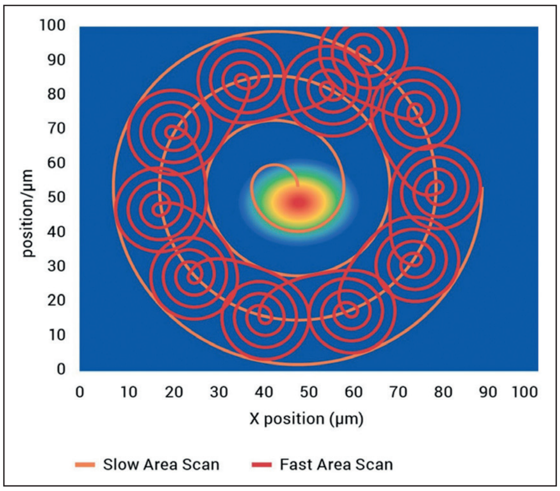


➤ Testing and packaging of modern photonic devices can be a huge challenge across multiple degrees of freedom. The alignment of multi-channel devices, such as fiber-optical arrays, used to be a slow, repetitive process before modern parallel algorithms were developed. (Image courtesy PI).

in the production process at the component positioning stage. Additionally, traditional assembly tools like shims and jigs may struggle to meet the increasingly stringent tolerances required for manufacturing modern devices. An alternative alignment strategy is necessary to precisely indicate component positioning.

Optical feedback to guide automatic alignment engines

A key characteristic of photonic devices is their efficiency's direct correlation with the alignment of individual components. This means that the output strength dynamically changes in real time with component positions. The varying signal strength serves as a guide for an iterative positional adjustment process, resulting in a precisely aligned assembly. To assess component drift, the fluctuation in photonic output strength can be monitored during the gluing and curing process. However, manually performing this method on complex devices with numerous inputs and outputs becomes impractical. Optimizing one connection can lead to movement affecting others, necessitating constant readjustment for a global consensus. An automated solution is essential to address this challenge, enabling a practical production process that eliminates the need for time-consuming back-and-forth adjustments.



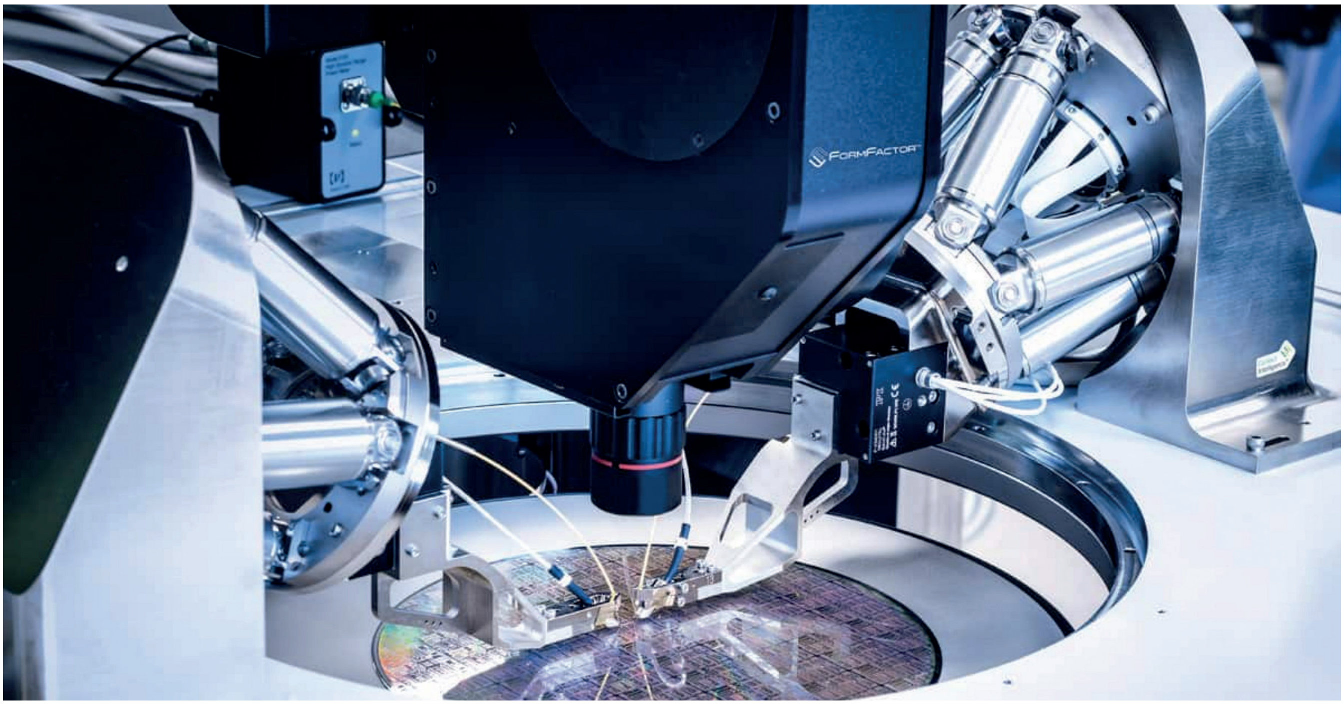
➤ Optical feedback is the key to automated alignment. A fast, traditional way of finding first light followed by a gradient search for optimum coupling efficiency is shown above – a double spiral scan using a hexapod/piezo approach. The hexapod runs a coarse spiral scan (coarse meaning single digit microns), while the piezo stage fills in the gaps with high-speed sub-micron scans. Both fine and coarse scans can be executed simultaneously. (Image courtesy PI)

Automating the adjustment process involves closing the feedback loop between device output and positioning hardware, allowing intelligent software solutions and control modules to handle fine-tuning. These systems utilize areal scan algorithms to characterize the assembly, identifying the approximate location of peak photonic output. Multiple gradient searches are then conducted to precisely determine the global optimum. Specialized piezo nano-positioning devices, capable of adjusting several connections simultaneously, guide the components into perfect alignment in an innovative process known as active alignment. Integrated features, including compensation factors, eliminate the need for constant iterative readjustment.

Complete modular solutions are now available, significantly reducing photonic device manufacturing times while maintaining sub-micron precision. Physik Instrumente's Fast Multichannel Photonic Alignment (FMPA) technology, for instance, can perform multiple alignments, such as in and outputs, across multiple-degrees of freedom, in parallel, reducing assembly time by a factor of 100 or more.

Solving the first light capture problem

Since alignment is the top cost driver for photonics device manufacturing, addressing it has been PI's



➤ The F-712, double-sided 18-axis fast multi-channel photonics alignment engine provides fast NxM alignment of SiP devices in wafer probers. The hexapods provide 6 degrees of freedom, while a compact 3-axis piezo scanner achieves nanometer resolution and scanning frequencies to 100Hz for fastest possible alignment. Cascade Microtech's pioneering CM300xi photonics-enabled engineering wafer probe station integrates PI's Fast Multichannel Photonics. Alignment engines for high throughput, wafer-safe, nano-precision optical probing of on-wafer Silicon Photonics devices. (Image courtesy FormFactor).

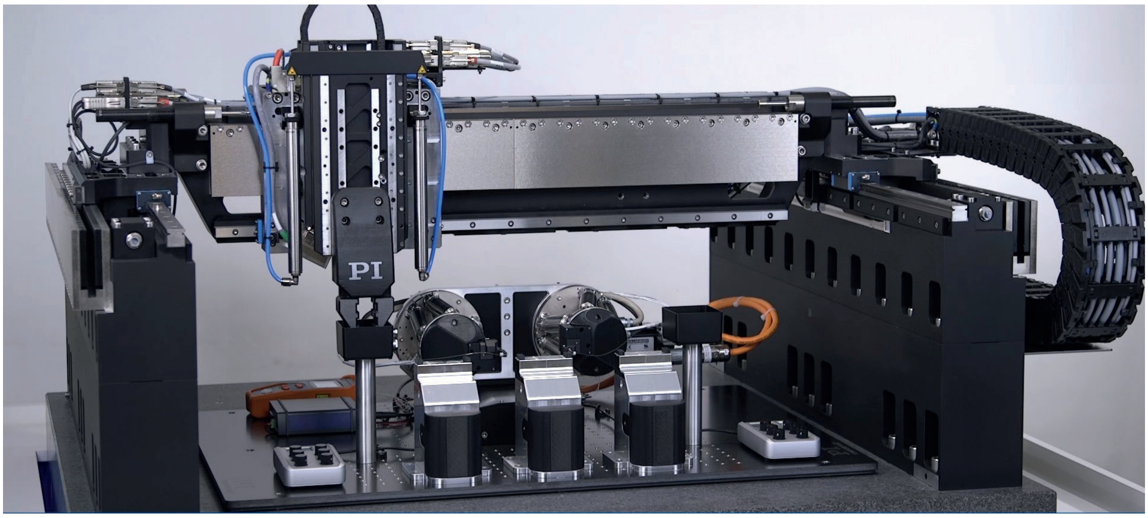
focus since the award-winning Fast Multichannel Photonics Alignment (FMPA) technologies in 2016. By performing optimization in parallel across multiple channels, components and degrees of freedom and achieving coupling repeatabilities to typically 0.02dB, FMPA reduces the time and cost of manufacturing and testing of photonic devices and improves yield. But before the optimization process can even start, an optical signal, above the noise level, needs to be detectable – this process is called first light capture, and it is particularly time-consuming in devices with inputs and outputs where both sides must be lined up for even a threshold amount of coupling to be achieved. Finding first light has been a time-consuming procedure in all industrial photonics alignment applications, including wafer probing and device packaging.

➤ A PILightning-algorithm enabled dual sided air-bearing-based alignment system. The new algorithm reduces the first light finding process in single-sided applications by 10X or more and in dual-sided applications by several 100X. (Image courtesy PI).

Now, a breakthrough has arrived in the form of a novel, built-in search-and-alignment algorithm (patent applied for), promising to revolutionize this field. The algorithm, dubbed PILightning runs embedded on PI's advanced controller. It enables highly dynamic mechanics such as piezo scanners or direct-drive air bearing stages to achieve significant production-economics gains over previous first light search algorithms. This new process is fully automated and virtually instantaneous, eliminating the need for extensive calibration or manual intervention. PILightning is based on a new search method with integrated AI-based real-time executive function. It also replaces fine pitch scanning by high frequency data sampling, raising alignment speeds significantly. It drastically reduces the time required to acquire first light in single- and double-sided couplings and in loopback (omega) waveguide configurations.

Once first light is detected, the FMPA fast gradient search algorithm takes over, utilizing real-time feedback control to swiftly optimize the alignment in parallel across the degrees-of-freedom and

➤ Image 6: A gantry pick-and-place system with two hexapod 6-axis high-speed automated alignment stations for fast SIPh component test. (Image courtesy PI)



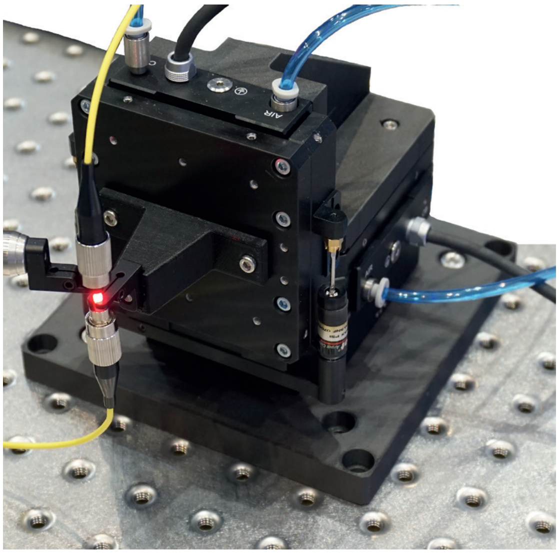
channels. Depending on the application, a tracking algorithm can also be activated to maintain maximum coupling efficiency – important, for example, in curing situations.

Ensuring future success through modular solutions based on multiple drive technologies

The photonics market is advancing rapidly, with projected substantial growth in a large number of sectors incorporating this technology in the next decade. Anticipating devices with hundreds or even thousands of individual components and connections, manufacturers face the necessity of parallel optimization, making active alignment the optimal choice to meet production demands.

Additionally, as photonic devices gain traction across various sectors, the development of increasingly specialized devices requires bespoke production processes. Manufacturers aiming to stay competitive and adapt to evolving demands require flexible combinations of hardware and software that can be easily reconfigured.

In addition to "monolithic" hexapod-based 6-axis alignment engines, modular alignment solutions,



➤ A compact, multi-axis air-bearing based photonics alignment system. Advantages of air bearings are frictionless, high-speed motion with virtually unlimited lifetime as well as the lack of particle generation. (Image courtesy PI).

exemplified by those developed by PI, excel in providing the flexibility and scalability necessary for production operations. These solutions include friction-free air-bearing-based motion systems that require zero maintenance and provide superior speed and lifetime, as well as linear and torque motor driven solutions with precision mechanical bearings, and economical systems based on traditional screw drives and stepper motors.

Common to all these modular systems is a high-performance EtherCat®-based motion controller with embedded, advanced alignment routines and integrated, high-speed optical power meter, for a quick path to success.

➤ PI's automation controller uses ACS controller and driver modules and embedded high-performance alignment algorithms for the highest data-throughput and shortest alignment times. EtherCat® connectivity allows seamless integration of third-party devices. (Image courtesy PI).

semi

Connecting Semiconductors and Electronics

About SEMI:
SEMI connects more than 2,500 member companies and 1.3 million professionals worldwide to advance the technology and business of electronics design and manufacturing. The breadth and depth of our events, programs and services help members accelerate innovation and collaboration on the toughest challenges to growth.

Electronic System Design Alliance

FlexTech

FOA Fab Owners Alliance

MEMS & SENSORS INDUSTRY GROUP®

SOI Industry Consortium

SMART MANUFACTURING

SMART MOBILITY

SMART MEDTECH

SMART DATA-AI

WORKFORCE DEVELOPMENT

Global ADVOCACY

Sustainability

MIT MARKET INTELLIGENCE TEAM

1000+ STANDARDS

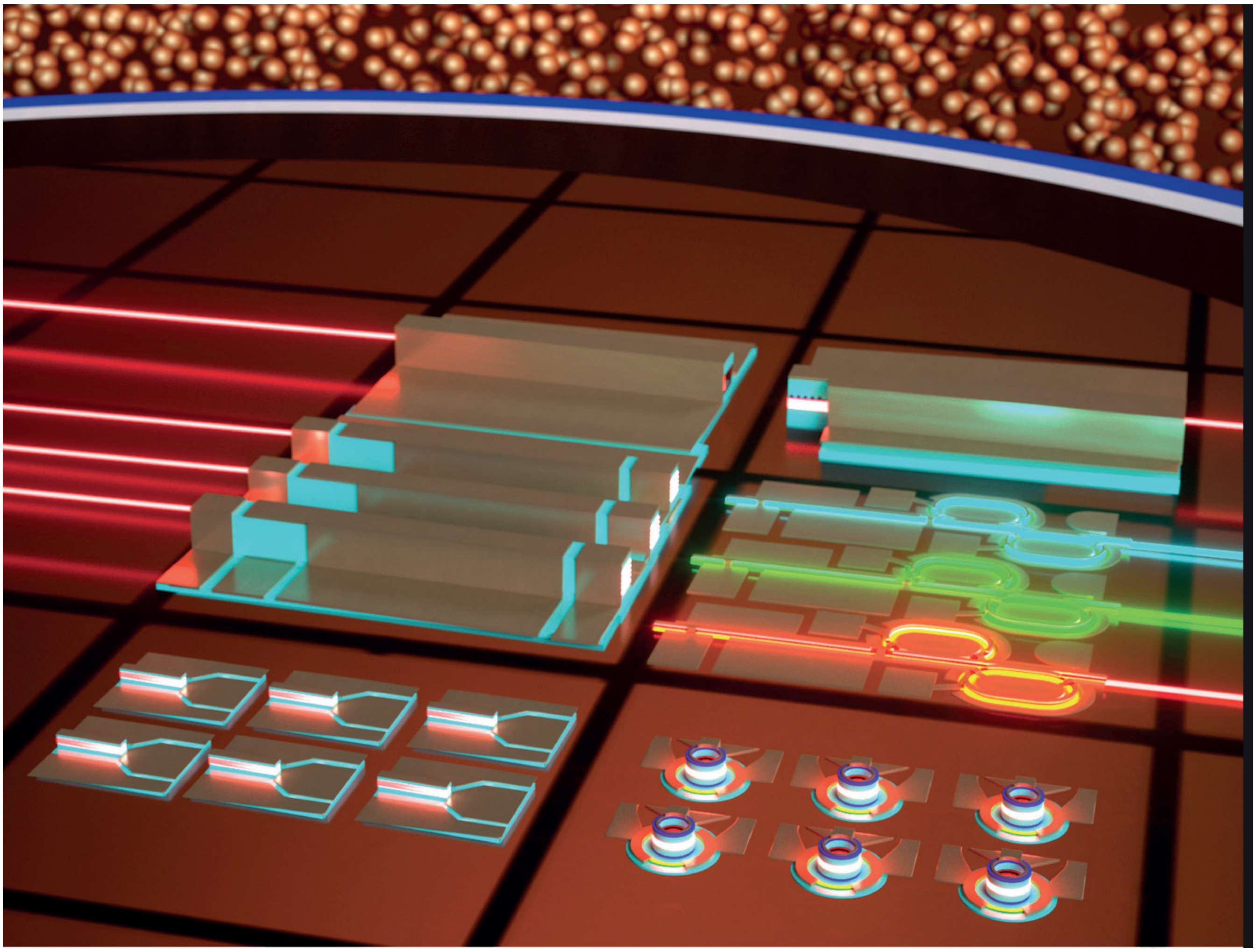
THOUGHT LEADERSHIP

SEMICON

TECH COMMUNITIES

SEMI UNIVERSITY

Cyber Security



Quantum-dot lasers on silicon

Integrating quantum-dot lasers on silicon photonic chips promises to create high-speed devices for datacom and other applications

BY ARTEM PROKOSHIN AND YATING WAN FROM KING ABDULLAH UNIVERSITY OF SCIENCE AND TECHNOLOGY

SINCE ITS INVENTION in 1962, the semiconductor laser has played a phenomenal role in changing our world. This source of monochromatic emission is now an essential component in CD and DVD players and recorders, laser printers, barcode readers, and most importantly, fibre-optic communication systems that connect our world through the internet.

Internet traffic continues to climb at an eye-watering pace, with analysts calculating a compound annual growth rate of 25 percent that, in 2022, propelled global traffic to 4.8 zettabytes – that's 4.8 trillion gigabytes. Given this tremendous rise in internet traffic, which shows no sign of abating, it is more important than ever to trim the power consumption of data transmitters and receivers. Efforts that are underway in that regard are not restricted to long-haul optical communications, and are also considering short-distance interconnects in datacentres, which now account for up to 2 percent of global electricity. The target is to drop below 1 picojoule per bit.

Fulfilling this goal will have far-reaching benefits. As well as helping to curb the carbon footprint in the datacom and telecom sectors, energy savings will help where there is a booming interest in the use of photonic chips in neural networks, known as photonic neural networks. With growing popularity of large language models, the cost of training and operating them is increasing. Photonic neural networks, driven by highly efficient semiconductor lasers, offer a promising solution to meeting this growing energy demand.

Helping to turn such dreams into reality by integrating quantum-dot lasers on silicon photonic chips is our team at the King Abdullah University of Science and Technology. By marrying these two technologies, we are uniting incredibly efficient sources with mature, high-volume semiconductor processing techniques.

Why silicon?

Silicon, by far the most widely used semiconductor material since the latter half of the last century, is the backbone of the microelectronics industry. When used to produce integrated photonics, silicon provides the most advanced material platform, developed over the last 20 years and relying heavily on CMOS technology. Merits of the silicon photonics platform include: a high refractive index contrast, leading to low-loss; high-confinement waveguides; and efficient grating couplers.

Drawing on silicon's doping technology, chipmakers can produce high-speed modulators based on *p-n* junctions, while this material's compatibility with germanium ensures fast and efficient silicon-germanium photodetectors. What's more, silicon photonics provides the highest manufacturing volume and the lowest cost, thanks to the opportunity to manufacture silicon chips on 300 mm wafers.

Unfortunately, despite all these strengths, silicon is not the perfect choice. Its biggest disadvantage for photonic applications is its indirect bandgap, preventing it from providing an efficient light source. While several silicon-germanium laser diodes have been demonstrated, they are unsuitable for real-world applications, due to their feeble output power and broad linewidth.

The lack of a silicon-based laser has led to the pursuit of two options for producing PICs with this material system. One involves combing silicon photonic chips, as purely passive devices, with an external light source. In this case, the downsides are high coupling losses, typically exceeding 3 dB, and increased packaging complexity. The second option is to integrate efficient lasers based on III-V semiconductors, such as GaAs or InP, directly onto silicon photonic chips. This approach reduces coupling loss to typically below 0.5 dB and simplifies packaging, but leads to constrained production volumes and increased costs.

Why quantum dots?

Since the introduction of the first semiconductor lasers, there have been a number of improvements to their design, along with the development of various different architectures. The first lasers were homojunction diodes, using the same material for the waveguide core material and its surroundings. To improve optical confinement, a breakthrough that ensured the first continuous-wave operation, engineers introduced a double heterostructure, sandwiching the active region between a pair of cladding layers with a wider bandgap and a lower refractive index. For example, this has been realised by surrounding a GaAs active region with AlGaAs. Another important advance followed, with a move to an active region employing a multiple quantum well structure that improves the efficiency of the radiative recombination process.

The next logical step, pursued by many in recent decades, is a move from a multi-quantum-well active region to one based on quantum dots. With this refinement, carrier confinement switches from one lateral direction to all three dimensions. Quantum dots, also referred to as 'zero-dimensional' structures, have dimensions on the order of tens of nanometres. They can be formed with a self-assembly process, involving epitaxial growth of InAs on a lattice-mismatched GaAs substrate.

The father of the quantum dot laser is Yasuhiko Arakawa from the University of Tokyo. In 1982 he proposed this device, claiming it had the potential to provide a lower threshold current and better temperature stability than its quantum-well-based cousins. Thanks to an atom-like structure and a discrete density of states, the quantum-dot laser provides an almost symmetric gain spectrum and a low linewidth enhancement factor, enabling narrow-linewidth and isolator-free operation. Additional opportunities for quantum dots are found in low-dark-current photodetectors and efficient Stark-effect amplitude modulators.

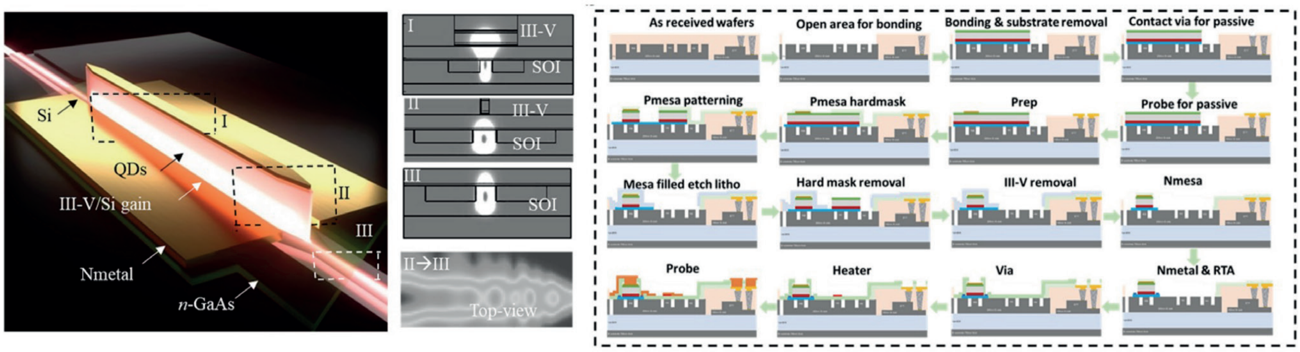


Figure 1. The fabrication process for quantum-dot lasers on silicon.

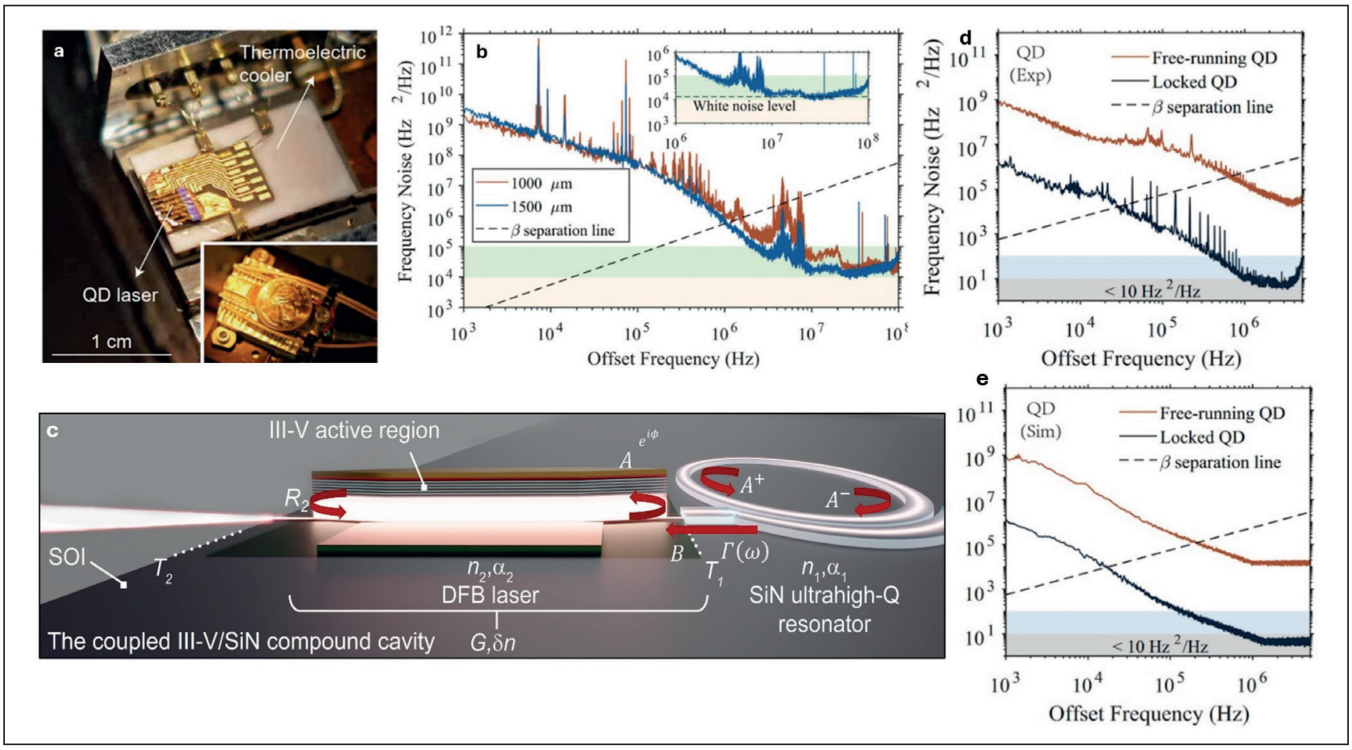


Figure 2. (a) QD laser mounted in a butterfly package. (b) Frequency noise spectra of QD lasers with a 1 mm and 1.5 mm long cavity. The linewidth in the free-running regime is 41 kHz. (c) Illustration of the coupled compound cavity. (h) and (i) Measured and calculated frequency noise spectra, indicating a fundamental linewidth of 16 Hz.

In the context of integration with silicon, the main advantage of quantum dots is a reduced sensitivity to crystal defects. These nanostructures offer improved in-plane carrier confinement, with diffusion lengths on the order of several microns – that compares with tens of microns in quantum wells, and ensures that dots are highly tolerant to dislocation defects.

The great potential of quantum dots is realised in devices. Measurements of quantum-dot lasers demonstrate that they can operate with a long extrapolated-lifetime at high temperatures, thus relaxing the stringent requirements on temperature control of photonic chips. This class of laser also offers a threshold current of less than 1 mA, making it an ideal candidate for addressing the ever-increasing energy consumption in optical communication networks.

Combining the two

When quantum dot lasers are integrated with silicon photonics, rather than being manufactured on native substrates, both improvements and drawbacks result. Focusing on the positives, there is the integration of quantum-dot active regions with high-quality grating structures and ring resonators to realise single-mode lasing. In addition, there is a lower propagation loss for silicon waveguides compared with III-V materials – this leads to lower threshold currents and a narrower linewidth for integrated lasers with an extended cavity.

Recently, we have directed our efforts at the heterogeneous integration of quantum-dot lasers on silicon via wafer bonding. This has involved the use of silicon-on-insulator substrates with a 500 nm-thick layer of silicon, which provides higher mode overlaps between the silicon and quantum-dot regions compared with the standard, 220 nm-thick silicon photonics platform.

Production of our PICs began with patterning our SOI wafer with three different etching depths: a 500 nm etch for strip waveguides, a 231 nm etch for rib waveguides, and a 20 nm etch for grating structures. Following this patterning process, we bonded our GaAs wafer to the quantum-dot active region, prior to annealing at 100°C and removing the GaAs substrate. GaAs mesas were then patterned to form laser active regions, followed by the deposition of the contact metal layer (see Figure 1 for a step-by-step illustration of the entire fabrication process).

With this approach, light generated in the quantum-dot active region is directed into the silicon waveguides by evanescent coupling. This occurs when two waveguides are close to each other – typically less than the wavelength of the light – a situation that allows light to transfer from one waveguide to another (see Figure 2). To increase coupling efficiency and cut back-reflections, we employ a taper rather than an abrupt transition between the III-V and the silicon waveguide. By terminating the silicon waveguide at the end of the chip with a 7° angled taper, we reduce back-reflection at the facets.

Our lasers achieve single-mode operation with a side-mode suppression ratio of over 60 dB (see Figure 3 (a)) and a threshold current of just 4 mA. The latter corresponds to a threshold current density of 31 A cm^{-2}, which is an order of magnitude lower than that of standard quantum-well lasers.

These directly modulated quantum-dot lasers are attractive candidates for datacentre communications, as they do not require additional modulators based on silicon or lithium niobate. However, due to a finite intraband relaxation time and gain saturation effects, it's a challenge to realise a high modulation bandwidth with quantum-dot lasers, with the 3 dB modulation frequency typically limited to around 10 GHz for devices grown on native substrates. However, thanks to synergistic effects between the silicon cavity and the quantum-dot active region, our heterogeneous quantum-dot device produces a modulation frequency of 13 GHz at an injection current of 31 mA (see Figure 3 (c)) for the corresponding small-signal response).

Another important characteristic for lasers used in optical communications is their linewidth, which indicates the noise level and ultimately limits data transmission capacity. QD lasers have a low linewidth enhancement factor, leading to narrower linewidths than the quantum-well counterparts. Early collaborative efforts have also spotlighted the unique properties of QD lasers in chaos-free operation, achieving a remarkably low 16 Hz Lorentzian linewidth under external-cavity locking with a low-Q cavity – an improvement in frequency noise by an order of magnitude over conventional quantum-well lasers. Standalone, these QD lasers (see Figure 2 (a)) exhibit a 41 kHz linewidth (see Figure 2 (b)). Under external optical feedback, a 35 dB improvement in feedback insensitivity has been achieved, enhancing stability and enabling operation without coherence collapse even with -9.6 dB of feedback. This makes the QD lasers suitable for integration into compact, highly integrated photonic systems without the need for optical isolators.

Looking ahead, there is theoretical potential for an even more dramatic reduction in linewidth – to 1 Hz or less – by employing a high-Q silicon-nitride--based micro-ring resonator in conjunction with the self-injection locking technique, as shown in Figure 2 (d) and (e). This prospective development is particularly suited for microwave photonics applications, including microwave synthesisers where stability is paramount.

Outstanding challenges

It is beyond question that quantum-dot lasers on silicon are a promising solution to addressing the growing energy demand in datacentre optical communications. These sources are markedly superior to their quantum-well counterparts in key performance criteria, including threshold current, linewidth and temperature stability. Additional merits of these lasers are a high output power and an exceptional modulation frequency.

Still, there is considerable work to do to make this technology viable and affordable in high-volume production. Efforts must be directed at realising wafer-scale integration on 300 mm substrates to fully exploit the high-volume, low-cost production capabilities of silicon photonics. Other outstanding goals are to integrate quantum-dot lasers with high-speed silicon modulators and photodetectors, and to undertake a systematic study of reliability with high-power testing, to prove that quantum-dot lasers can deliver reliable operation at the elevated temperatures found in data centres. Once these tasks have been accomplished, the next step will be to demonstrate a platform that is best at leveraging the economies-of-scale of silicon while maintaining the highest yield at the lowest lifecycle cost.

The capability of our technology allows its opportunities to stretch beyond datacentres. The realisation of the dense integration of devices with on-chip lasers is an advance that will prove crucial in many of tomorrow's applications, including photonic neural networks, biochemical sensing and quantum computing. The addition of on-chip laser sources enables all-optical signals to be confined within an integrated circuit package, enhancing efficiency, stability, and scalability. This integration is poised to revolutionise many applications, while offering significant performance improvements, environmentally friendly solutions, and the potential for mass production.

FURTHER READING / REFERENCE

- Y. Arakawa *et al*. "Multidimensional quantum well laser and temperature dependence of its threshold current" Appl. Phys. Lett. **40** 939 (1982)
- Y. Wan *et al*. "High speed evanescent quantum-dot lasers on Si." Laser Photonics Rev. **15** 2100057 (2021)
- Z. Zhou *et al*. "Prospects and applications of on-chip lasers". eLight **3** 1 (2023)
- R. Koscica *et al*. "Heterogeneous integration of a III–V quantum dot laser on high thermal conductivity silicon carbide." Opt. Lett. **48** 2539 (2023)
- C. Xiang *et al*. "High-Performance Silicon Photonics Using Heterogeneous Integration." IEEE J. Sel. Top. Quantum Electron. **28** 3 (2022)
- C. Shang *et al*. "Perspectives on Advances in Quantum Dot Lasers and Integration with Si Photonic Integrated Circuits." ACS Photonics **8** 2555 (2021)
- Y. Wan *et al*. "Quantum Dot Lasers and Amplifiers on Silicon: Recent Advances and Future Developments." IEEE Nanotechnol. Mag. **15** 8 (2021)
- W. W. Chow *et al*. "Analysis of the spontaneous emission limited linewidth of an integrated III–V/SiN laser." Laser Photonics Rev. **16** 2100620 (2022)

To promote your products and services contact:
Shehzad Munshi
T: +44 (0)1923 69015
E: shehzad.munshi@angelbc.com

Avo Photonics
PIC Packaging Services
Tel: +1 215-441-0107
eillg@avophotonics.com
www.avophotonics.com

EPIC
European Photonics Industry Consortium
www.epic-assoc.com

EXFO
Tel: +1 418-683-0211
francois.couny@exfo.com
www.exfo.com/en

ficonTEC
micro assembly machines
Tel: +49 4202 51160-435
info@ficontec.com
www.ficontec.com

IQE
http://www.iqep.com

LIGENTEC
info@ligentec.com
www.ligentec.com

LUCEDA PHOTONICS
Tel: +32 (0) 52 339 838
erwin@lucedaphotonics.com
www.lucedaphotonics.com/en

lumerical
Tel +1(604) 733-9006
info@lumerical.com
www.lumerical.com

Optiwave
Tel:+1-613-224-4700*249
sawyer.ge@optiwave.com
www.optiwave.com

PI
Tel: +49 721 4846 1802
j.denzer@pi.de
www.physikinstrumente.com/en

VPIphotonics
DESIGN AUTOMATION
Tel: +1-781-762-3901 / +49-30-398058-0
info_pic@VPIphotonics.com
www.vpiphotonics.com

PICMAGAZINE
To advertise here call
Shehzad Munshi
+44 (0)1923 690215
shehzad.munshi@angelbc.com

Showcase your presence to the global Photonics industry for 12 months

PIC MAGAZINE is the primary information resource for professionals working with PIC materials and devices.

Each issue of the magazine is distributed digitally to over 15,000+ professionals worldwide.

With the largest and most diverse global audience of qualified buyers served by any photonic focused magazine, secure a corporate partnership and buyers guide entry and receive 12 months of promotion and exposure to the PIC industry across the magazine portfolio including:

- 12 months of promotion in quarterly issues of the digital and PDF magazine featuring your company logo and company details
- 12 months of promotion and exposure on the PIC Magazine website **www.picmagazine.net** featuring a Buyers Guide entry and hyperlinked company logo
- Sponsorship of one e-news alerts sent out to over 15,000 industry professionals with text and a standard web banner.

To find out more, contact: Shehzad Munshi
E: shehzad.munshi@angelbc.com
T: +44 (0)1923 690215


ASMPT
enabling the digital world
EMPOWERING SILICON PHOTONICS AND CO-PACKAGED OPTICS PACKAGES
© shutterstock
AI
AMICRA NANO
ASMPT
AMICRA NOVA
ASMPT
AMICRA NANO
AMICRA NOVA PRO
Visit ASMPT AMICRA
at Booth # B126
asmpt.com
amicra.semi.asmpt.com
50th Anniversary
ECOC 2024
FRANKFURT
EXHIBITION 23–25 SEPTEMBER