PIC MAGAZINE

CONNECTING THE PHOTONIC INTEGRATED CIRCUITS COMMUNITY

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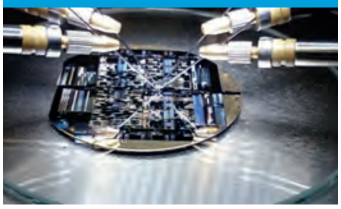
Collaboration supply chain for photonic packaging

PIC-Enabled CVD Detectors

Plug and play characterization



Comb lasers advanced high-performance

Using MBE to grow 2D crystals

Fast test needed for virus detection using integrated photonic biosensors

By EPIC

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Viewpoint

By Mark Andrews, Technical Editor

PIC technologies and 2020's new normal

RECENTLY, new work-from-home devices were welcome yet routine product announcements while today they gain outsized notoriety. Six months ago, 'pandemic' was only an epidemiological topic. Now, huge numbers of photonics designers, developers and integrators are working remotely due to the SARS-CoV-2 virus. This is 2020's New Normal.

While many of us are still striving to achieve balance between important and sometimes conflicting objectives, the pandemic has given everyone a new perspective on what is important including the health we previously took for granted, family connections, and a collective future still being written.

No matter what is happening around us, technology remains a societal 'glue' enabling all types of work and life scenarios unimagined mere months ago. Back in 2003, when interviewing with a major manufacturer, part of that meeting was conducted using what was then emerging video conferencing tech—it took an IT specialist (on both ends) and high-speed fiber to enable needed throughput. Today, hundreds of thousands of meetings are handled through Zoom or Teams using laptop cameras and low-cost peripherals. Even while tech industries face unprecedented challenges, they are also realizing new opportunities: we find community through video conferencing; we find hope in social media posts by friends and family.

In this issue of PIC Magazine, EPIC's R&D Manager, Ana Gonzalez, reports on PIC-enabled technologies for faster, medically accurate biosensing. New generations of pathogen detection systems are emerging using PICs and other

photonic sensors even as we fight COVID-19. LIGENTEC describes its new heater modules for PICs offering four-times the performance of standard SiN heaters. We look at the next stage of clinical trials for the handheld CARDIS cardio vascular disease (CVD) detection device. We also explore advances in comb lasers and their role in high-performance computing. As TAP automation remains a vital need within PIC manufacturing, we explore plug-and-play chip level test and characterization through the Fraunhofer Heinrich Hertz Institute's integrated electrical test platform.

'Business Unusual' has challenged us like never before. But we have also seen resilience across industries, demonstrating how we can productively live and work safely, even within our very changed world. Stay safe!

Editor Jackie Cannon | jackie.cannon@angelbc.com | +44 (0)1923 690205
Editor Mark Andrews | mark.andrews@amcsolutions.info
Contributing Editor Rebecca Pool | editorial@rebeccapool.com
News Editor Christine Evans-Pughe | chrise-p@dircon.co.uk
Sales Executive Jessica Harrison | jessica.harrison@angelbc.com | +44 (0)2476 718209
USA Representatives Tom Brun Brun Media | tbrun@brunmedia.com | +001 724 539-2404
Janice Jenkins | jjenkins@brunmedia.com | +001 724-929-3550
Publisher Jackie Cannon | jackie.cannon@angelbc.com | +44 (0)1923 690205
Director of Logistics Sharon Cowley | sharon.cowley@angelbc.com | +44 (0)1923 690200
Design & Production Manager Mitch Gaynor | mitch.gaynor@angelbc.com | +44 (0)1923 690214

Circulation Director Scott Adams | scott.adams@angelbc.com | +44 (0)2476 718970
Chief Executive Officer Stephen Whitehurst | stephen.whitehurst@angelbc.com | +44 (0)2476 718970
Joint Managing Director Sukhi Bhadal | sukhi.bhadal@angelbc.com | +44 (0)2476 718970
Joint Managing Director Scott Adams | scott.adams@angelbc.com | +44 (0)2476 718970
Directors Jackie Cannon, Sharon Cowleyl

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

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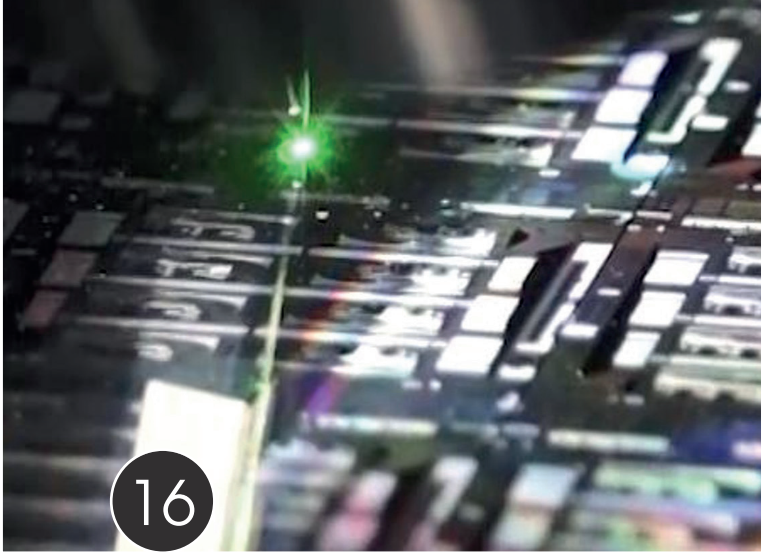

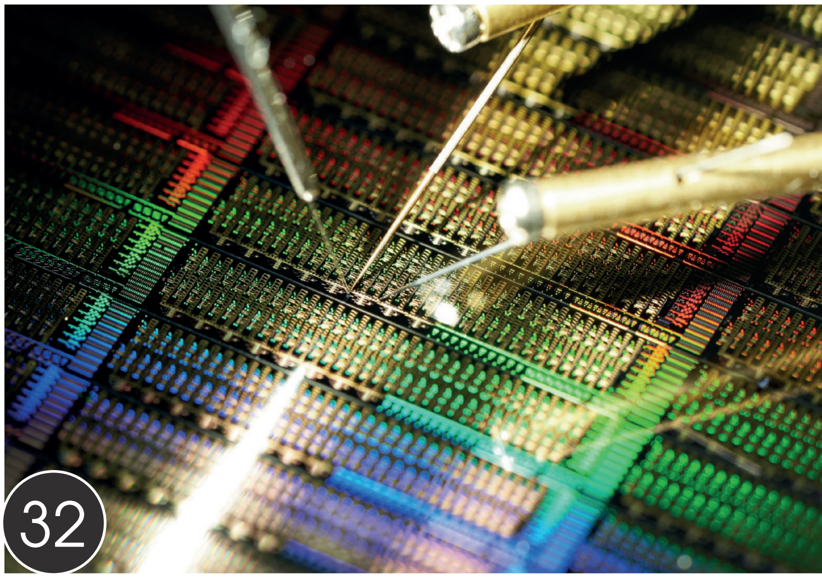

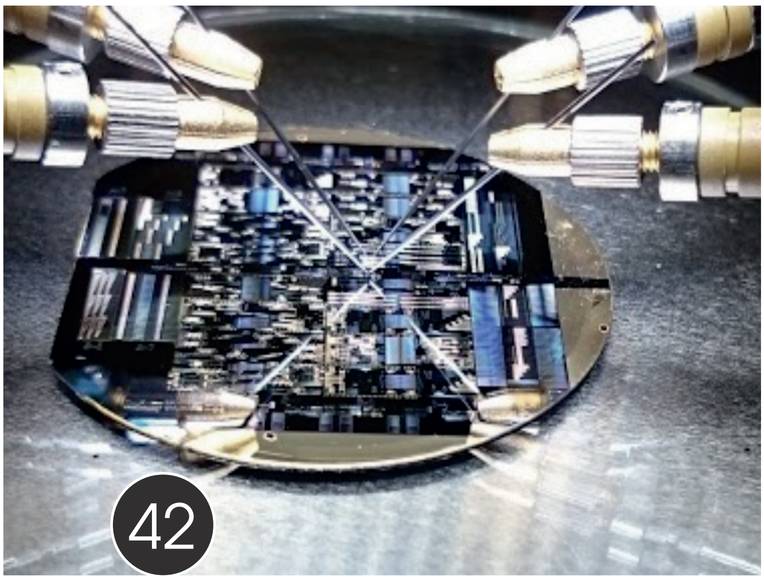

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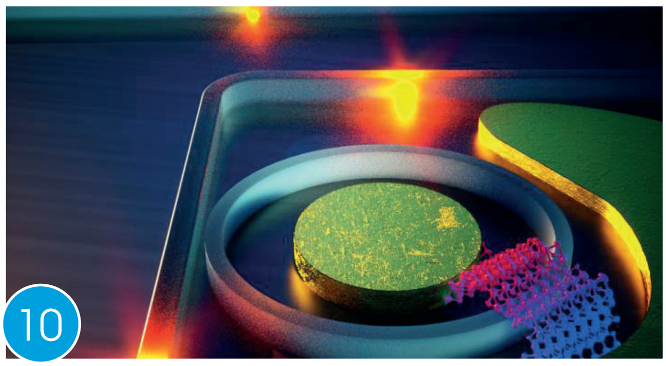


Shedding new light on nanolasers

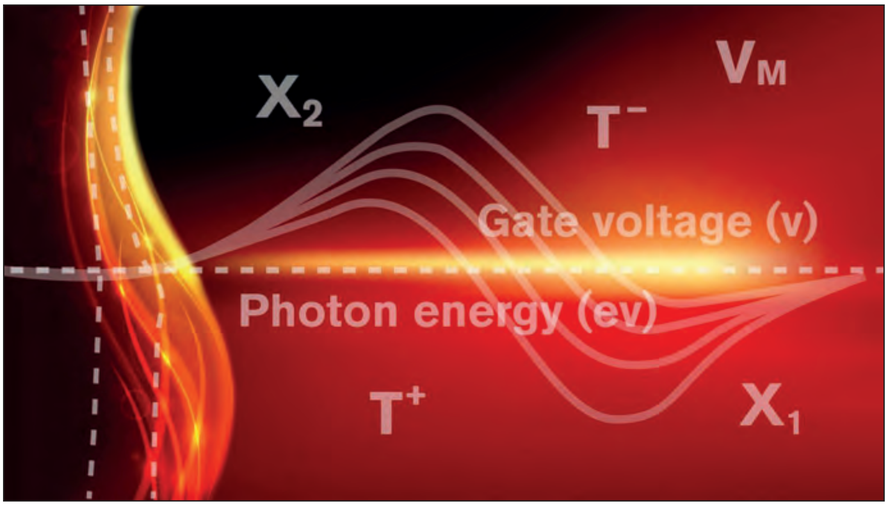
IN HIS LATEST LINE of research, Cun-Zheng Ning, a professor of electrical engineering in the Ira A. Fulton Schools of Engineering at Arizona State University, and his peers explored the intricate balance of physics that governs how electrons, holes, excitons and trions coexist and mutually convert into each other to produce optical gain. Their results, led by Tsinghua University Associate Professor Hao Sun, were recently published in the Nature publication Light: Science & Applications.

"While studying the fundamental optical processes of how a trion can emit a photon [a particle of light] or absorb a photon, we discovered that optical gain can exist when we have sufficient trion population," Ning says. "Furthermore, the threshold value for the existence of such optical gain can be arbitrarily small, only limited by our measurement system."

In Ning's experiment, the team measured optical gain at density levels four to five orders of magnitude smaller than those in conventional semiconductors.

Ning is interested in a phenomenon called the Mott transition, an unresolved puzzle in physics about how excitons form trions and conduct electricity in semiconductor materials to the point that they reach the Mott density (the point at which a semiconductor changes from an insulator to a conductor and optical gain first occurs). But the electrical power needed to achieve Mott transition and density is far more than what is desirable for the future of efficient computing. Without new low-power nanolaser capabilities like the ones he is researching, Ning says it would take a small power station to operate one supercomputer.

"If optical gain can be achieved with excitonic complexes below the Mott transition, at low levels of power input, future amplifiers and lasers could be made that would require a small amount of driving power," Ning says. This development could be game-changing for energy-efficient photonics, or light-based devices, and provide an alternative to conventional semiconductors, which are limited in their ability to create and maintain enough excitons.



As Ning observed in previous experiments with 2D materials, it is possible to achieve optical gain earlier than previously believed. Now he and his team have uncovered a mechanism that could make it work. "Because of the thinness of the materials, electrons and holes attract each other hundreds of times stronger than in conventional semiconductors," Ning says. "Such strong charge interactions make excitons and trions very stable even at room temperatures." This means the research team could explore the balance of the electrons, holes, excitons and trions as well as control their conversion to achieve optical gain at very low levels of density.

"When more electrons are in the trion state than their original electron state, a condition called population inversion occurs," Ning says. "More photons can be emitted than absorbed, leading to a process called stimulated emission and optical amplification or gain." While this new discovery added a piece to the Mott transition puzzle - it uncovered a new mechanism that researchers can exploit to create low-power 2D semiconductor nanolasers - Ning says that they are not yet sure if this is the same mechanism that led to the production of their 2017 nanolasers.

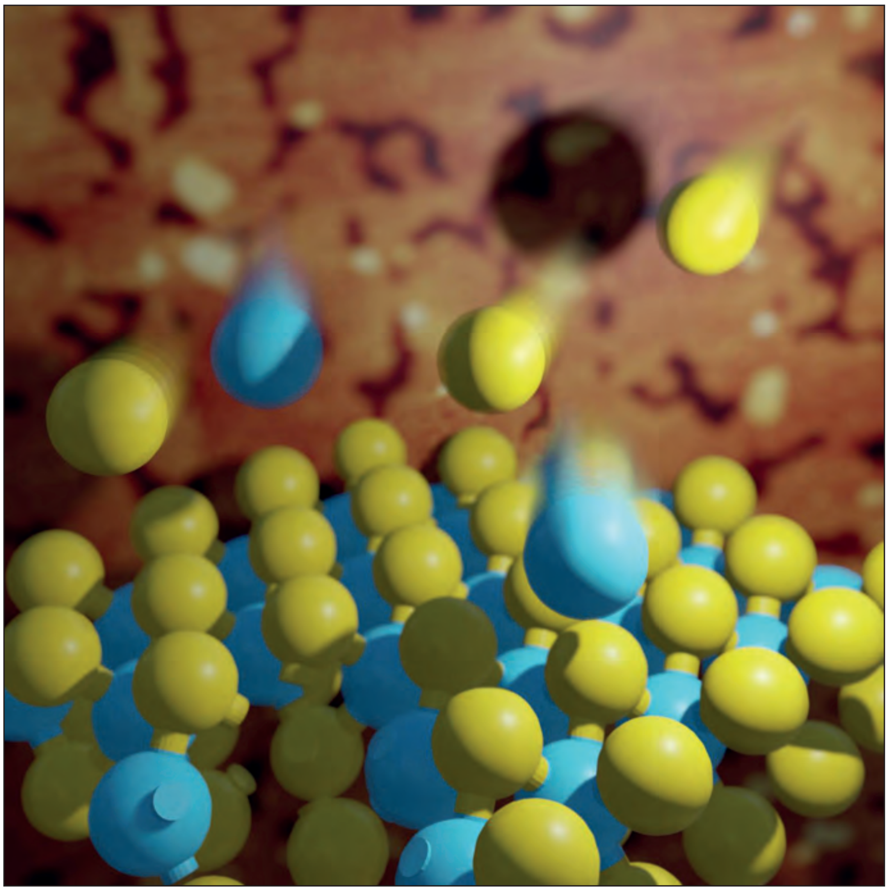
Similar trion experiments were conducted in the 1990s with conventional semiconductors, Ning says, "but the excitons and trions were so unstable, both experimental observation and, especially, utilisation of this optical gain mechanism for real devices are extremely difficult." "Since the excitons and trions are much more stable in the 2D materials, there are new opportunities to make real-world devices out of these observations."

This interesting development by Ning and his research team is only at the fundamental science level. However, fundamental research can lead to exciting things. "Basic science is a worldwide endeavour and everyone benefits if the best people from everywhere can be involved. ASU has provided an open and free environment, especially for international collaborations with top research groups in China, Germany, Japan and worldwide," Ning says.

His team has more work left to do to study how this new mechanism of optical gain works at different temperatures - and how to use it to create the nanolasers purposefully. "The next step is to design lasers that can operate specifically using the new mechanisms of optical gain," Ning says. "The long-term dream is to combine lasers and electronic devices in a single integrated platform, to enable a supercomputer or data centre on a chip," Ning says. "For such future applications, our present semiconductor lasers are still too large to be integrated with electronic devices." 'Excitonic complexes and optical gain in two-dimensional molybdenum ditelluride well below the Mott transition' by Zhen Wang et al; Light: Science & Applications volume 9, Article number: 39 (2020)

Using MBE to grow 2D crystals with excellent optical properties

A team of physicists from the University of Warsaw have grown monolayers of transition metal dichalcogenides (TMDs) with excellent optical properties. Using MBE on atomically flat BN substrates, they managed to overcome the technical difficulties of limited size, heterogeneity, and broadening of the spectral lines of fabricated materials that have so far confounded other researchers. The results were published in Nano Letters.



2D crystals with a honeycomb structure, including the famous graphene, show huge promise for future electronic and optoelectronic applications. However, despite substantial investments in the development of growth techniques for atomically thin crystals, the best quality monolayers are currently still obtained using exfoliation, i.e. due to the mechanical detachment of individual atomic layers from the bulk crystal.

For example, graphene flakes exfoliated from bulk graphite exhibit superior electrical properties when compared to grown graphene. In contrast, the size of the mechanically exfoliated monolayers is rather small.

Similarly, optical properties of 2D TMDs (such as MoSe2) are fully revealed only for layers obtained as a result of exfoliation and after having been subjected to further mechanical treatment, such as placing them between layers of BN. However, as already mentioned, this technique does not lead to atomically thin crystals on a larger scale, resulting in heterogeneity, limited size, and even to the appearance of corrugations, bubbles, and irregular edges.

Hence, it is crucial to develop a technique for growing 2D TMDs that will allow for the production of monolayers with a large surface area. Currently, one of the most advanced technologies for producing thin semiconductor crystals is MBE. It provides low-dimensional structures on large wafers, with high homogeneity, but its effectiveness in the production of TMDs has been very limited so far. In particular, the optical properties of MBE grown monolayers have hitherto been rather modest, e.g. spectral lines have been broad and weak, giving no hope for the use of the spectacular optical properties of TMDs on a larger scale.

It is in this area that researchers from the Faculty of Physics of the University of Warsaw made a breakthrough. In collaboration with several laboratories from Europe and Japan, they conducted a series of studies on the growth of TMDs monolayers on an atomically flat BN substrate. In this way, using the MBE method, they obtained flat crystals, equal in size to the substrate, showing uniform parameters over the entire surface, including - most valuably - excellent optical properties.

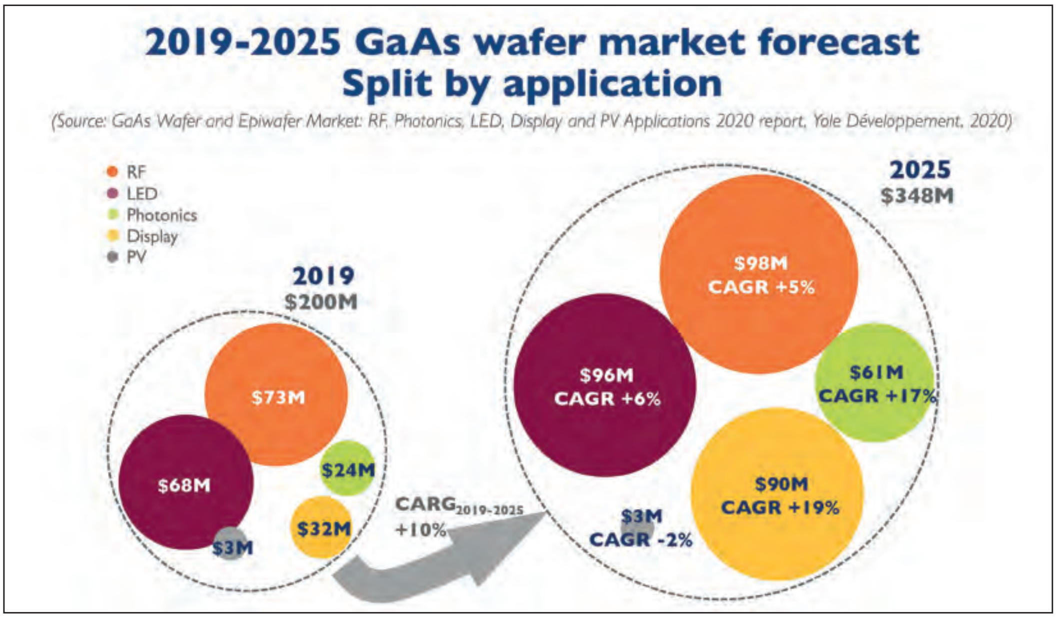
The picture above is an artistic visualisation of a monolayer of 2D MoSe2 grown by directing molecular beams of selenium (yellow) and molybdenum (blue) on atomically flat hexagonal BN substrate. Thanks to this substrate, MoSe2 epilayer exhibits excellent optical properties.

The discovery directs future research into the industrial production of atomically thin materials. In particular, it indicates the need to develop larger atomically flat BN wafers. On such wafers, it will be possible to grow monolayers with the optical quality, dimensions, and homogeneity required for optoelectronic applications.

‘Narrow Excitonic Lines and Large-Scale Homogeneity of Transition-Metal Dichalcogenide Monolayers Grown by Molecular Beam Epitaxy on Hexagonal BN’ by

W. Pacuski et al; ACS Nano Lett. 20, 3058 (2020).

GaAs: technical breakthroughs pushed by photonics



IN THE PAST FEW YEARS, the GaAs wafer market has been dominated by RF applications. As of 2020, according Yole Développement's latest research, photonics and LEDs represent the main drivers for this markets.

The new study forecasts the the total GaAs wafer market will increase from $200 million in 2019 to more than $348 million by 2025, with a CAGR of 10 percent.

Ezgi Dogmus, member of the Power & Wireless division at Yole said: "RF is the historical market driver for GaAs wafers. In 2019 it represented 33 percent of market volume and 37 percent of market value. RF represents 67 percent of the GaAs epiwafer open market. GaAs RF demand is mainly driven by handset evolution, with the transition to 5G resulting in greater penetration of GaAs PAs for the high-end sub-6GHz phones".

In parallel, photonics has a 5 percent share of wafer volume, corresponding to a $24 million market. However, the photonics market will have a double digit CAGR2019-2025, with GaAs VCSEL technology strongly dominating this market. In this context, photonics applications represent 32 percent of the GaAs epiwafer open market.

With the transition of LEDs from low-end applications to high-end applications, such as horticulture lighting or automotive, LEDs still represent the highest GaAs wafer market volume with 41 percent share. Automotive will be the main driver for visible LEDs and IR LEDs, with a dynamic 6 percent CAGR envisaged from 2019 to 2025.

GaAs will find another source of growth in the display market, driven by hot new applications such as microLEDs. Yole analysts forecast the CAGR of the display market to be 19 percent in the 2019-2025 timeframe.

Without doubt consumer and automotive market segments will be strongly modified by the COVID-19 crisis. Consequently, the compound semiconductor team from Yole decided to include three different scenarios in its GaAs technology & market report, especially focused on the market evolution and production recovery.

In the mobile market segment, Yole predicts the most likely scenario is an estimated 20 percent production drop in 2020 as compared to 2019. Analysts also notice that some major OEM s, such as Samsung and Apple, have re-positioned their products. In fact, OEMs expect a shift from high end to middle end and even entry level smartphones, due to a reduction of household revenue. Regarding automotive applications, Yole forecasts a production drop around 30 percent...

From a supply chain point of view, the GaAs epiwafer supply chain is constantly changing.

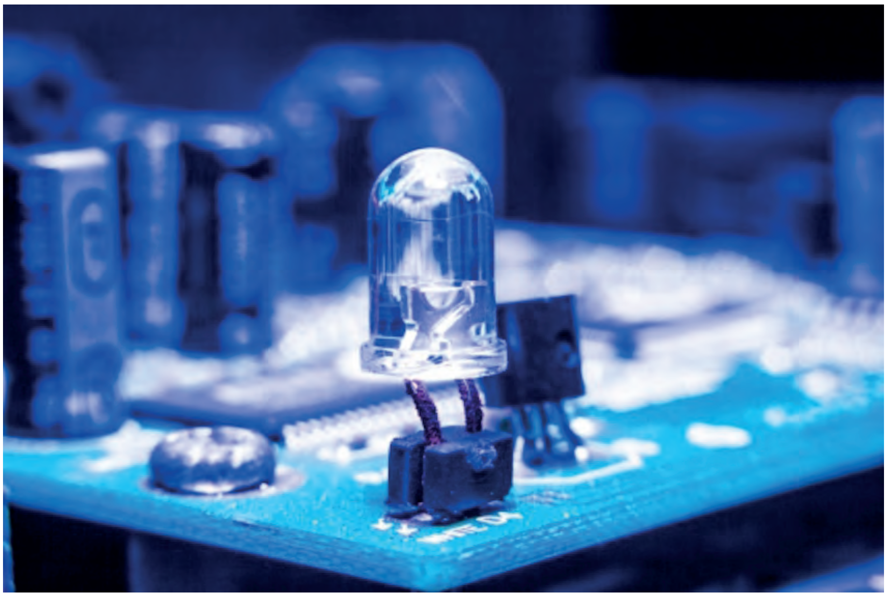
Yole analyst Ahmed Ben Slimane explains: "In the photonics market, the epiwafer business model is application dependent. In datacom, it is mostly integrated, dominated by Finisar, Avago and II-VI. However, for 3D sensing and other VCSELs for smartphones, manufacturers prefer to outsource the epitaxy, a less complicated strategy adopted by Apple, which is supplied by IQE. IQE remains the biggest epiwafer supplier, with 61 percent photonic epiwafer market share in 2019. But, with increased adoption of 3D sensing, numerous players such as VPEC, II-VI, Sumitomo Chemicals and Landmark are ramping up their production".

The RF GaAs epitaxy market is about 90 percent outsourced. Previously it was largely dominated by IQE, nevertheless it has lost share to the Chinese-Taiwanese supply chain. As of 2019, IQE and VPEC represent more than 80 percent of the RF epi market. The LED epiwafer market remains almost entirely integrated within very well-established companies like Osram, San'an, Epistar, and Changelight.

In terms of GaAs wafer supply, Freiberger, Sumitomo Electric, AXT and Vital Materials lead the market in 2019. The top players have a bigger market share in high end applications, and due to stringent laser grade wafer specifications, they will keep their advantage for the next 5-8 years.

The outlook for new Chinese GaAs suppliers is challenging, they recently entered the market with low-end products for LED. However, their transition to high-end products and expansion out of China is risky due to potential IP infringement issues.

Giving photons a sense of direction for better LEDs



UC SANTA BARBARA researchers continue to push the boundaries of LED design a little further with a new method that could pave the way toward more efficient and versatile LED display and lighting technology.

In a paper published in Nature Photonics, UCSB electrical and computer engineering professor Jonathan Schuller and collaborators describe this new approach, which could allow a wide variety of LED devices - from virtual reality headsets to automotive lighting - to become more sophisticated and sleeker at the same time.

"What we showed is a new kind of photonic architecture that not only allows you to extract more photons, but also to direct them where you want," said Schuller. This improved performance, he explained, is achieved without the external packaging components that are often used to manipulate the light emitted by LEDs.

Light in LEDs is generated in the semiconductor material when excited, negatively charged electrons traveling along the semiconductor's crystal lattice meet positively-charged holes (an absence of electrons) and transition to a lower state of energy, releasing a photon along the way.

Over the course of their measurements, the researchers found that a significant amount of these photons were being generated but were not making it out of the LED.

"We realised that if you looked at the angular distribution of the emitted photon before patterning, it tended to peak at a certain direction that would normally be trapped within the LED structure," Schuller said. "And so we realised that you could design around that normally trapped light using traditional metasurface concepts."

The design they settled upon consists of an array of 1.45-micrometer long GaN nanorods on a sapphire substrate, in which quantum wells of InGaN were embedded, to confine electrons and holes and thus emit light. In addition to allowing more light to leave the semiconductor structure, the process polarises the light, which co-lead author Prasad Iyer said, "is critical for a lot of applications."

Nanoscale Antennae
The idea for the project came to Iyer a couple of years ago as he was completing his doctorate in Schuller's lab, where the research is focused on photonics technology and optical phenomena at subwavelength scales. Metasurfaces - engineered surfaces with nanoscale features that interact with light - were the focus of his research.

"A metasurface is essentially a subwavelength array of antennas," said Iyer, who previously was researching how to steer laser beams with metasurfaces. He understood that typical metasurfaces rely on the highly directional properties of the incoming laser beam to produce a highly directed outgoing beam.

LEDs, on the other hand, emit spontaneous light, as opposed to the laser's stimulated, coherent light. "Spontaneous emission samples all the possible ways the photon is allowed to go," Schuller explained, so the light appears as a spray of photons traveling in all possible directions. The question was could they, through careful nanoscale design and fabrication of the semiconductor surface, herd the generated photons in a desired direction?

"People have done patterning of LEDs previously," Iyer said, but those efforts invariably split the into multiple directions, with low efficiency. "Nobody had engineered a way to control the emission of light from an LED into a single direction."

Right Place, Right Time
It was a puzzle that would not have found a solution, Iyer said, without the help of a team of expert collaborators. GaN is exceptionally difficult to work with and requires specialized processes to make high-quality crystals. Only a few places in the world have the expertise to fabricate the material in such exacting design.

UC Santa Barbara, home to the Solid State Lighting and Energy Electronics Center (SSLEEC), is one of those places, say the researchers. With the expertise at SSLEEC and the campus's world-class nanofabrication facility, the researchers designed and patterned the semiconductor surface to adapt the metasurface concept for spontaneous light emission.

"We were very fortunate to collaborate with the world experts in making these things," Schuller said.

'Unidirectional luminescence from InGaN/GaN quantum-well metasurfaces' by Prasad P. Iyer et al; Nature Photonics 01 June (2020)

POET and Sanan IC to form $50M joint venture

POET Technologies, a developer of the POET Optical Interposer and PICs for data centre and telecomms markets, has signed a Letter of Intent to establish a joint venture with Chinese firm Xiamen Sanan to manufacture cost-effective, high-performance optical engines based on POET˙s proprietary CMOS compatible Optical Interposer platform technology.

The proposed joint venture will be formed with contributions of $50 million based on a combined commitment of cash and intellectual property from Sanan IC and intellectual property and know-how from POET.

Sanan IC is a wafer foundry service company with an advanced compound semiconductor technology platform, serving the optical, RF microelectronics and power electronics markets. Sanan IC is a wholly owned subsidiary of Sanan Optoelectronics, a manufacturer of LED epitaxial wafers and chips. The venture is expected to design, develop, manufacture and sell 100G, 200G and 400G optical engines with customised lasers and photodiodes from Sanan IC combined with optical interposer platform technology from POET. Based on know-how from both companies, such optical engines are engineered for high yield and large-scale to meet the burgeoning market for high-speed data communications applications, including internet data centres and 5G carrier networks.

"Combining the advanced wafer foundry manufacturing platform capabilities of Sanan IC with the true wafer-scale and hybrid integration approach of the POET Optical Interposer platform, we will be able to offer transceiver manufacturers the ability to span several generations of devices and unlimited scale for high-volume applications at a highly economical price," said Suresh Venkatesan, chairman and CEO of POET. "Sanan IC is the world˙s preeminent manufacturer of compound semiconductors, and we are excited to partner with them in delivering our next generation solutions."

"This joint venture has the potential to have a breakthrough on technological innovation as well as product competitiveness," said Raymond Cai, CEO of Sanan IC. "We will employ Sanan IC˙s flexibility and experience in customised lasers and photo diodes with our advanced foundry manufacturing platform capability and extensive capacity with POET˙s Optical Interposer platform to enable our joint venture company to offer the market the highest performance optical engines at a competitive price. As a premiere foundry service provider for compound semiconductor wafers, we are pleased to partner with POET on a joint venture to deploy these technologies."

The global market for optical transceivers is estimated to be $5.7 billion in 2020 and projected to reach a value of $9.2 billion by 2025, representing a CAGR of 10.0 percent, according to MarketsandMarkets Research Private Ltd.

CEA-Leti demo full data-transfer silicon photonics module

CEA-Leti announced the demonstration of a fully packaged CWDM optical transceiver module with data transfer of 100 Gb/s per fiber with a low-power-consumption electronic chip co-integrated on the photonic chip. This silicon-photonics-based transceiver multiplexes two wavelengths at 50 Gb/s and is designed to meet the ever-increasing data-communication demands and energy use of data centers and supercomputers.

The EU H2020 project, COSMICC, further developed all the required building blocks for a transmission rate of 200 Gb/s and beyond without temperature control with four 50-Gb/s wavelengths and by aggregating a large number of fibers. The key breakthroughs are the development of broadband and temperature-insensitive silicon nitride (SiN) multiplexing components on silicon (Si), the integration of hybrid III-V/Si lasers on the Si/SiN chips and a new high-count adiabatic fiber-coupling technique via SiN and polymer waveguides.

This demonstration opens the way to technology that allows a reduction in the cost, the power consumption and the packaging complexity and opens the way to reaching a very high aggregated data rate beyond terabits per second (Tb/s).

Starting with STMicroelectronics' silicon photonics integration platform, the COSMICC project developed a coarse wavelength division multiplexing (CWDM) silicon-photonics transceiver in a packaged module at 100 Gb/s per fiber. It is scalable to 400 Gb/s and includes 3D assembly of a silicon photonic chip and its electronic control chip. The silicon photonic chip integrated high-performance 50 Gb/s NRZ optical modulators and photodetectors, and a two-channel CWDM multiplexer and demultiplexer. The control electronics was optimized to minimize energy consumption down to 5.7 pJ/bit per channel at 50 Gb/s data rate.

Separately, a library of enabling building blocks for higher data-rate datacenter interconnects was built on a SiN-enhanced silicon photonics platform, including new broadband and athermal SiN components and hybrid III-V/Si lasers. SiN, which is 10 times less sensitive to temperature than silicon, will dramatically reduce the transceiver cost and power consumption by eliminating the need for temperature control and will thus contribute to the reduction of the heat output and cooling costs of mega datacenters. CEA-Leti scientist Ségolène Olivier, who coordinated the EU project, said development of modulators and photodetectors at 50 Gb/s and their co-integration with their control electronics was a breakthrough that led to the low-power consumption 100 Gb/s transceiver module.

"In addition, the new building blocks are essential for addressing the need for terabit-per-second transceivers at low cost and low energy consumption to sustain the exponential growth of data traffic in datacenters and in high performance computing systems," she explained.

Scientists grow optical chips in a petri dish

A team of scientists led by researchers at ITMO in St Petersburg, Russia, have proposed a quick and affordable method to create miniature optical chips in a Petri dish. The research was published in ACS Nano.

Today's optical chips operate in the infrared (IR) range. "To make the devices even more compact, we need to work in the visible range," says Sergey Makarov, chief researcher at ITMO's Department of Physics and Engineering, "as the size of a chip depends on the wavelength of its emission."

Creating a light source that would emit in the green or red part of the spectrum is quite easy, however, waveguides for these wavelengths can be an issue. Ivan Sinev, senior researcher at ITMO's Department of Physics and Engineering said: "The standard silicon waveguides that are used in IR optics do not work in the visible range. They transmit the signal no further than several micrometers. For an optical chip, we need to transmit along tens of micrometers with a high localisation, so that the waveguide would have a very small diameter and the light would go sufficiently far through it."

Silver waveguides were considered but the transmission distance was insufficient. In the end, they used GaP as a material for the waveguides, as it has very low losses in the visible band and long-range guiding over distances more than 20μm. But the most important thing, they say, is that both the light source can be grown directly on a waveguide in a Petri dish using solution chemistry methods, which is cheaper than the commonly used nanolithography. So in their chip, they embedded the GaP nanowires directly into compact $CsPbBr_3$-based light sources. The perovskite microcrystals support stable room-temperature lasing and broadband chemical tuning of the emission wavelength in range 530–680 nm, while the GaP nanowaveguides support efficient outcoupling of light.

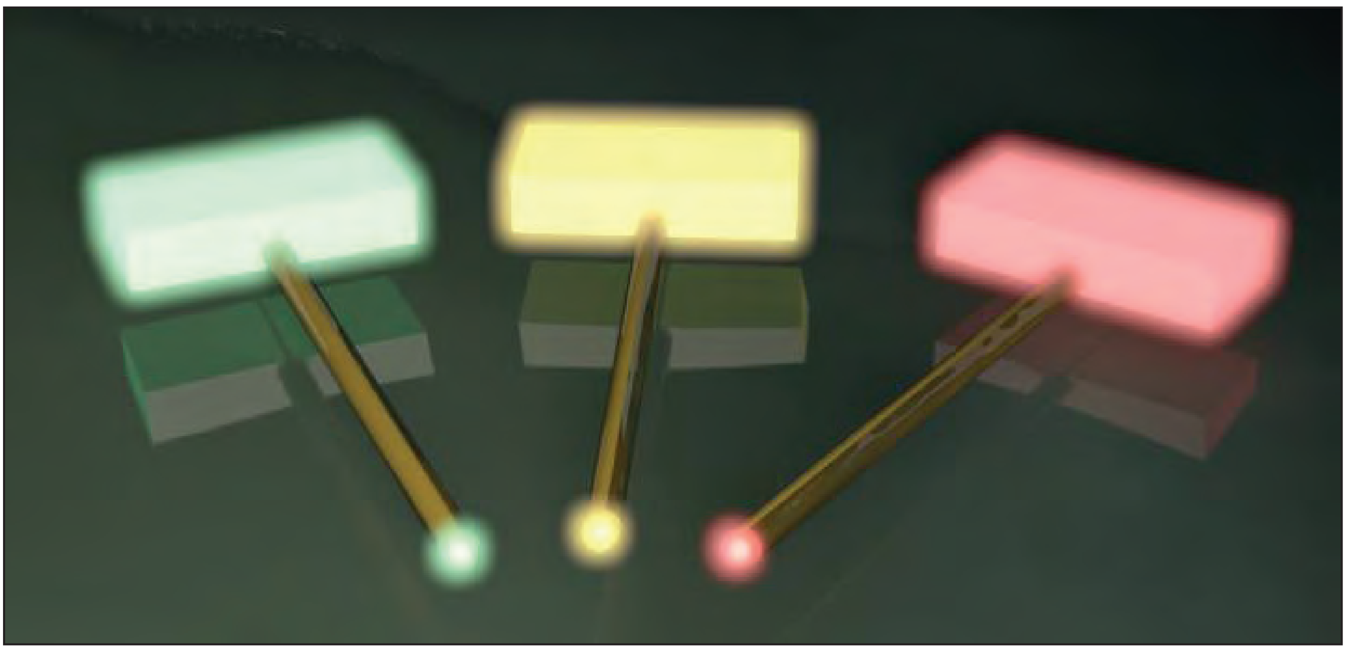
The size of the new chip's elements is about three times smaller than that of its counterparts that work in the IR spectral range.

"The chip's important property is its ability to tune the emission colour from green to red by using a very simple procedure: an anionic exchange between perovskite and hydrogen halides vapour," notes Anatoly Pushkarev, senior researcher at ITMO's Department of Physics and Engineering. "Importantly, you can change the emission colour after the chip's production, and this process is reversible. This could be useful for the devices that have to transmit many optical signals at different wavelengths. For example, you can create several lasers for such a device, connect them to a single waveguide, and use it for transmitting several signals of different colors at once."

The scientists also equipped the newly created chip with an optical nanoantenna made of perovskite that receives the signal travelling along the waveguide and allows uniting two chips in a single system.

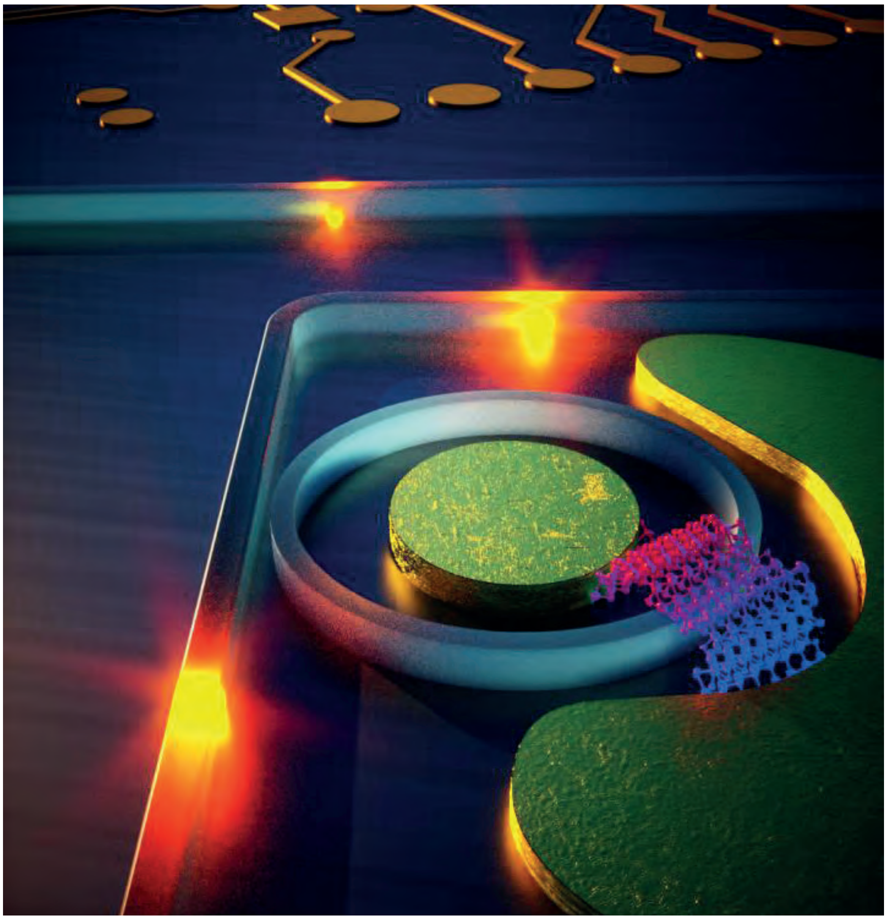
"We added a nanoantenna at the other end of our waveguide," explains Pavel Trofimov, PhD student at ITMO's Department of Physics and Engineering, "so now we have a light source, a waveguide, and a nanoantenna that emits light when pumped by the microlaser's emission. We added another waveguide to it: as a result, the emission from a single laser went into two waveguides. At the same time, the nanoantenna did not just connect these elements into a single system, but also converted part of the green light into the red spectrum."

'Perovskite - Gallium Phosphide Platform for Reconfigurable Visible-Light Nanophotonic Chip' by Pavel Trofimov et al; ACS Nano, June 15, 2020



Strainoptronics: A new way to control photons

Scientists have discovered a new way to engineer optoelectronic devices by stretching a 2D compound semiconductor on top of a silicon photonic platform. THey published the results in Nature Photonics.



Using this method, coined strainoptronics by a team led by George Washington University professor Volker Sorger, the researchers demonstrated for the first time that a 2D material wrapped around a nanoscale silicon photonic waveguide creates a novel photodetector that can operate with high efficiency at the technology-critical wavelength of 1550 nanometers.

The ever-increasing data demand of modern societies requires a more efficient conversion of data signals in the optical domain, from fibre optic internet to electronic devices, like a smartphone or laptop. This conversion process from optical to electrical signals is performed by a photodetector, a critical building block in optical networks.

2D materials have scientific and technologically relevant properties for photodetectors. Because of their strong optical absorption, designing a 2D material-based photodetector would enable an improved photo-conversion, and hence more efficient data transmission and telecommunications. However, 2D semiconducting materials, such as those from the family of transition metal dichalcogenides, have, so far, been unable to operate efficiently at telecommunication wavelengths because of their large optical bandgap and low absorption.

Strainoptronics provides a solution to this shortcoming and adds an engineering tool for researchers to modify the electrical and optical properties of 2D materials, and thus the pioneered 2D material-based photodetectors.

Realising the potential of strainoptronics, the team which included scientists from the universities of Pennsylvania, Texas, Minnesota and Ghent, stretched an ultrathin layer of $MoTe_2$, a 2D material semiconductor, on top of a silicon photonic waveguide to assemble a novel photodetector. They then used their newly created strainoptronics 'control knob' to alter its physical properties to shrink the electronic bandgap, allowing the device to operate at near infrared wavelengths, namely at the telecommunication (C-band) relevant wavelength around 1550 nm.

The researchers noted one interesting aspect of their discovery: the amount of strain these semiconductor 2D materials can bear is significantly higher when compared to bulk materials for a given amount of strain. They also note these novel 2D material-based photodetectors are 1,000 times more sensitive compared to other photodetectors using graphene. Photodetectors capable of such extreme sensitivity are useful not only for data communication applications but also for medical sensing and possibly even quantum information systems.

"We not only found a new way to engineer a photodetector, but also discovered a novel design methodology for optoelectronic devices, which we termed 'strainoptronics.' These devices bear unique properties for optical data communication and for emerging photonic artificial neural networks used in machine learning and AI", said Volker Sorger, associate professor of electrical and computer engineering at GW.

"Interestingly, unlike bulk materials, 2D materials are particularly promising candidates for strain engineering because they can withstand larger amounts of strain before rupture. In the near future, we want to apply strain dynamically to many other 2D materials in the hopes of findi ng endless possibilities to optimize photonic devices, " said Rishi Maiti, postdoctoral fellow in the electrical and computer engineering department at GW

'Strain-Engineered High Responsivity MoTe2 Photodetector for Silicon Photonic Integrated Circuits' by R, Maiti et al; Nature Photonics, Monday, June 22, 2020

W-WDM MSA Group to drive laser standards

THE CW-WDM MSA (Continuous-Wave Wavelength Division Multiplexing Multi-Source Agreement) Group has announced its formation as an industry consortium dedicated to defining and promoting specifications for multi-wavelength advanced integrated optics.

IEEE and MSA standards specify four WDM interfaces for today's high volume datacom optics. Emerging advanced integrated optics applications, such as silicon photonics (SiPh) based high-density co-packaged optics, optical computing, and AI, are expected to move to 8, 16, and 32 wavelengths.

Standardising higher wavelength counts is a crucial part of an emerging ecosystem which is enabling a leap in efficiency, cost, and bandwidth scaling compared to current technology. Increasing the number of wavelengths, while staying in the O-band and aligning with ITU and IEEE standards, allows developers and suppliers to leverage their strategic investments in the current generation of optical products to accelerate time to market of next generation products.

"We support and encourage consortiums like the CW-WDM MSA Group in order to accelerate important technical innovations," said Christopher Berner, head of compute at OpenAI. "OpenAI must be on the cutting edge of AI capabilities and low latency, high bandwidth optical interconnect is a central piece of our compute strategy to achieve our mission of delivering artificial intelligence technology that benefits all of humanity."

The CW-WDM MSA is different from optical communication standards groups in that it solely focuses on specifying the laser source instead of the full communications link, and is not targeted at any specific application.

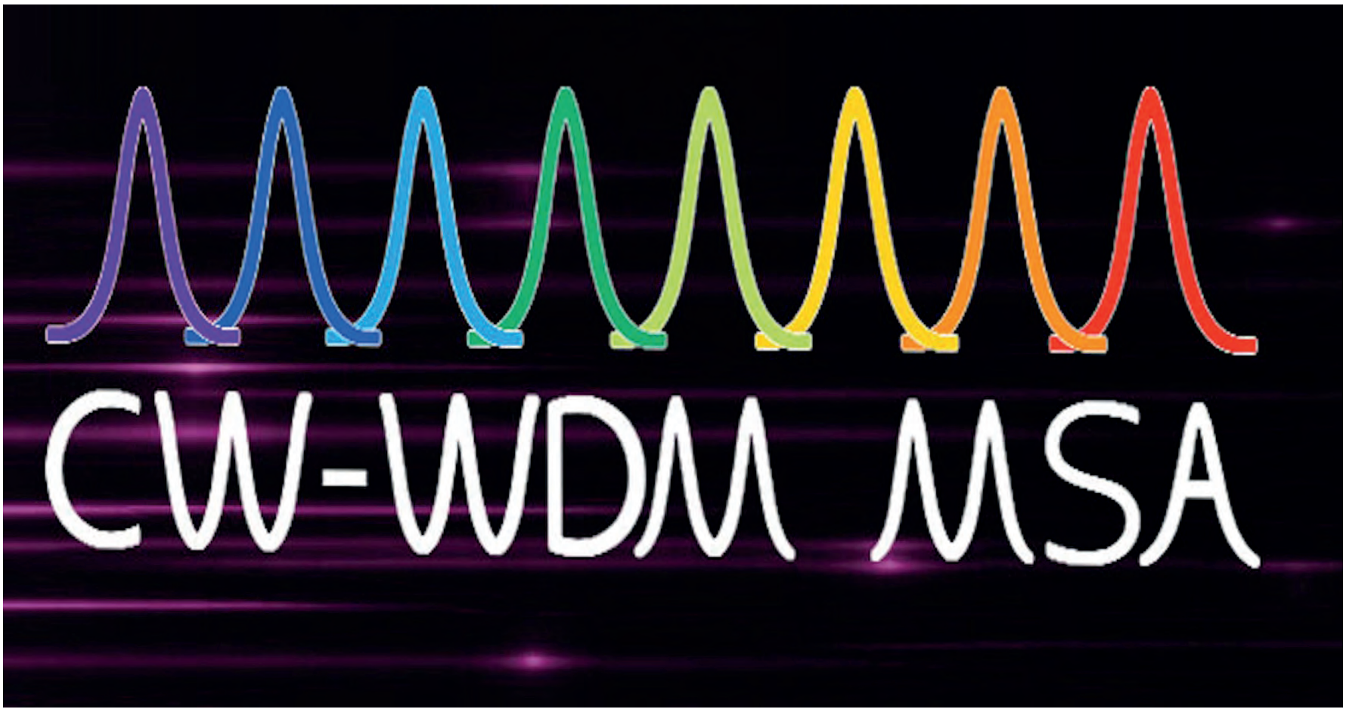
Such an approach allows developers to fully optimise optics to their customers' requirements without interoperability constraints while simultaneously creating a large business opportunity for laser source suppliers.

"Laser sources have been the critical building block of fibre optic communications, and standardising their specifications has been key to the success of telecom and datacom optics," said Chris Cole, chair of the CW-WDM MSA. "ITU-T established complete baselines for DWDM and CWDM grids. The IEEE then specified subsets of these grids for high volume data centre applications, starting with 40G and 100G Ethernet optics. The CW-WDM MSA will similarly leverage ITU-T and IEEE standards to specify 8, 16 and 32 wavelength grids in O-band for emerging advanced datacom and computing optics. With the definition of multiple grid sets, the MSA will enable developers to choose what is optimum for their application, while allowing laser suppliers to only have to invest in one technology platform."

Promoter Members of the CW-WDM MSA are Arista Networks, Ayar Labs, CST Global, imec, Intel, Lumentum, Luminous Computing, Macom, Quintessent, Sumitomo Electric, and II-VI.

In addition, several Observer Members have signed on to be briefed on the development of the standard to enable early technology development based on the new specifications.

Observer Members are AMF, Axalume, Broadcom, Coherent Solutions, Furukawa Electric, GlobalFoundries, Keysight Technologies, NeoPhotonics, NVIDIA, Samtec, Scintil Photonics, and Tektronix.



LIGENTEC adds wide tuning rage heater modules to its product lineup

LIGENTEC, a specialist foundry delivering innovative, low loss, thick silicon nitride (SiN) services for photonic integrated circuit designers and manufacturers, has added a next-generation heater module for its 'All-Nitride' line of process services. The new heater module was developed using Lumerical's Device Suite of photonic simulation software.

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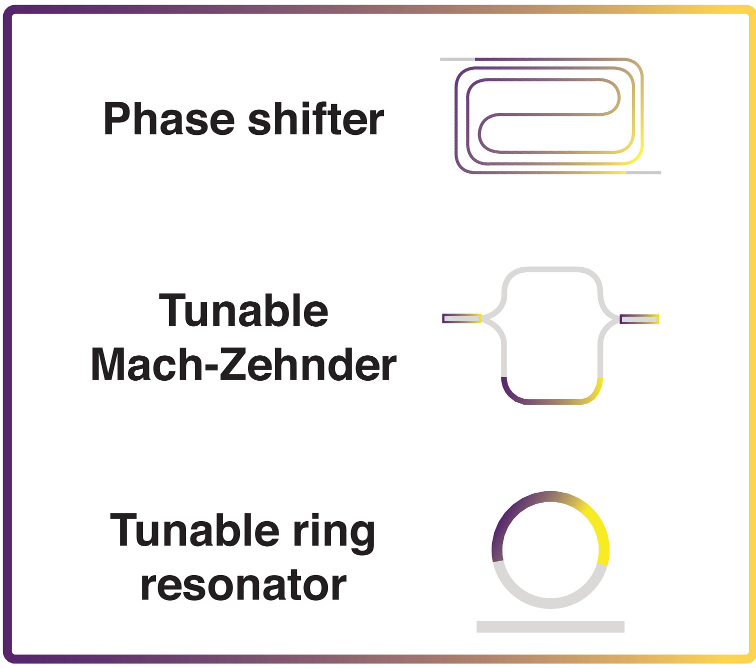
According to the company, LIGENTEC's advanced heater module provides four times more thermo-optical tuning and improved stability for tunable ring resonators and Mach Zehnder Interferometers (MZI) than standard heaters developed in silicon nitride. Development of the new heater module was customer driven – LIGENTEC indicated their customer needed a large tuning range for a ring resonator that was not available with other heater materials. In their application the material needed to reach a temperature over 300° C to achieve the large tuning range that they needed.

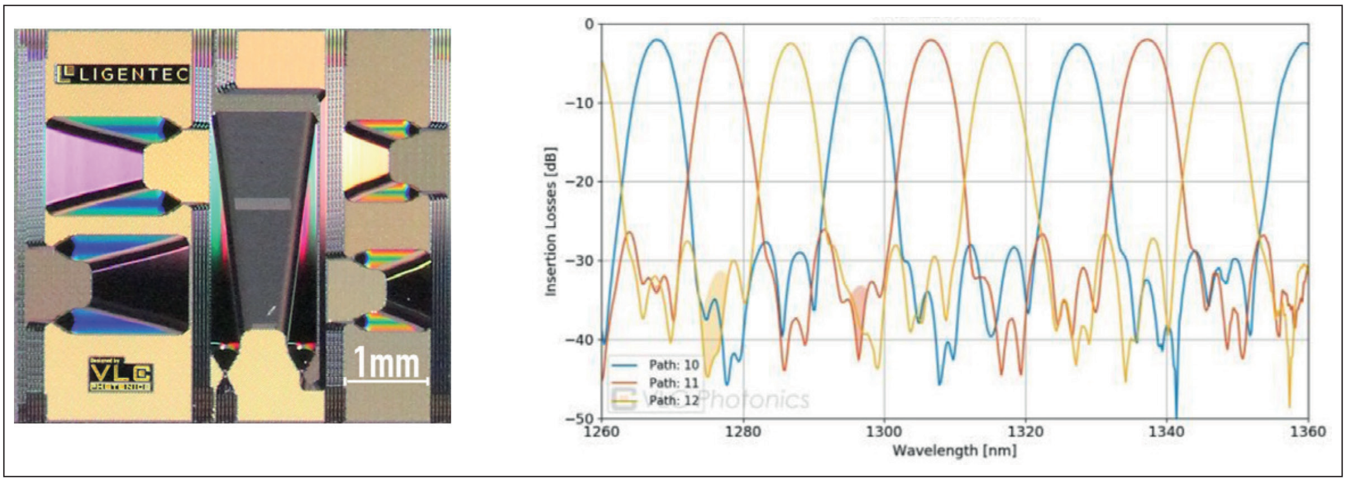
"The new advanced heater module gives access to very high local temperatures and in such a way can heat the silicon nitride waveguide and change its temperature-dependent refractive index. For example, it is used to tune wavelength selective filters by large tuning ranges, MZIs by several pi phase shifts, long delay lines by long phase shifts or ring resonators for frequency comb generation by more than one full free spectral range obtaining more than 4nm of tuning. This is used for telecom and datacom applications as well as spectroscopy and metrology where large tuning ranges are needed," stated Dr. Michael Geiselmann, Managing Director.

The newly available heater module is optimized for LIGENTEC's all-nitride AN800 process with waveguides that offer low bending radii (< 0.005 dB for 10 turns of 50um radius), low coupling losses (< 1 dB/facet), low propagation losses (< 0.1 dB/cm) and high power handling (up to 10 W tested). The company said that the heater material can support very high temperatures.

Compared to aluminum based heater materials, LIGENTEC's product is much more stable at high



Advanced heater module for long range thermal tuning: Sketch of three application cases utilizing the advanced heater module. From left to right: Long phase shifts in optical delay lines; more than 4Pi shifts in MZIs; and large tuning range of ring resonators for filters or for shifting the resonances of a generated optical frequency comb.



temperatures: above 500° C. Furthermore, it is fully compatible with large scale CMOS fabrication lines, which makes scaling to volume easy.

Designed using Lumerical's DEVICE Suite, the LIGENTEC heater module is responsive and stable over an ultra-broad tuning range. According to the company, a ring resonator with a free spectral range (FSR) of 500 GHz (resonance separation of 4 nm) can be tuned by more than 4 nm operating at telecom wavelength range, thus covering a full tuning of the FSR. Similarly for MZIs, multiple pi-phase shifts are possible.

The company indicated that Lumerical's simulation tool, DEVICE HEAT, was essential to the design phase of product development since it takes into account the material properties and heat coefficients of silicon nitride and glass, linking these factors directly to the optical mode problem solver within the design software.

Lumerical's DEVICE Suite performs multiphysics simulation of heat and electrical conduction, combined with photonics simulation, including relevant material models in each physical domain.

TESTED EXEMPLARY PERFORMANCES

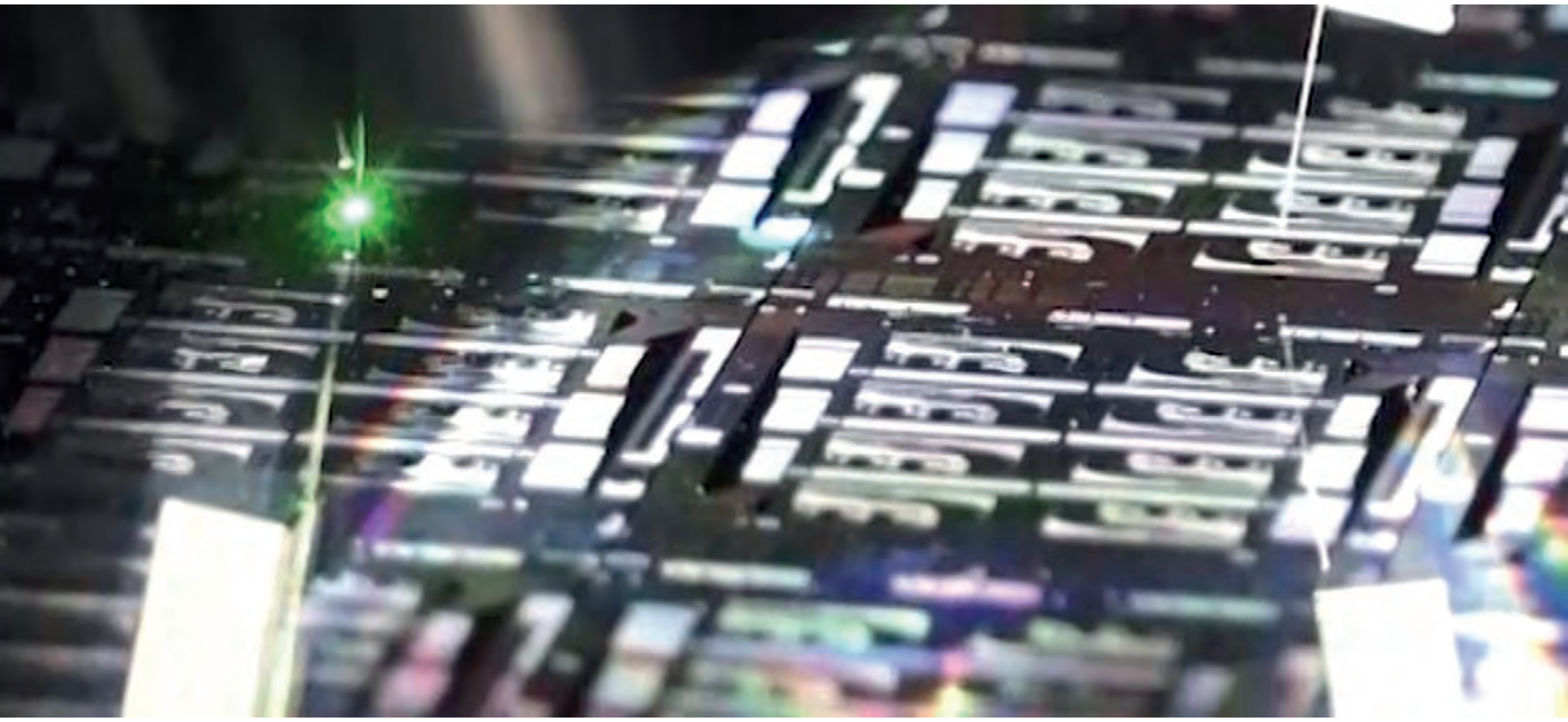
Wavelength	O-band	C-band	900 nm
Insertion loss	1 dB	1.5 dB	4 dB
Crosstalk	35 dB	30 dB	35 dB
Channel spacing	4.6 nm 10 nm	6 nm	4 nm 10 nm 20 nm
Shape	Gaussian	Flat-top	Gaussian
FSR	18.4 nm 30 nm	24 nm 48 nm	30 nm 70 nm 140 nm
Chip size	2 x 2 mm	1 x 2 mm	1 x 2 mm

Designed and measured by VLC Photonics

It is an ideal platform for designing photonic integrated circuits (PICs) targeted for LIGENTEC's All-Nitride (AN) process. Due to the significantly low loss characteristic of LIGENTEC's AN core technology, the fidelity of imported material data is critical to simulation quality. With its HEAT and CHARGE solvers, Lumerical's DEVICE Suite provides multiphysics simulation capabilities and workflows to model the interaction between optical, electrical and thermal effects at the physical level.

About Ligentec

LIGENTEC specializes in low loss photonic integrated circuits for customers developing products for a wide-range of applications including integrated quantum optics, LiDAR, sensors and microwave photonics. LIGENTEC commercializes all-nitride-core technology; the company received a PIC Award at the PIC International Conference in 2018. Its technology uses thick film optical grade LPCVD deposited silicon nitride and optimized cladding to provide guaranteed performance in propagation loss. Through its all-nitride (AN) technology, LIGENTEC enables customers to develop their products to support Industry 4.0 applications and a wide range of other products where PICs offer advantages such as smaller size, high data rate, wide bandwidth and immunity to EMI. Customers benefit from the fact that LIGENTEC provides a clear path to volume production. The company offers multi project wafer (MPW) foundry options to keep costs low, as well as the ability to serve the needs of company's requiring dedicated wafer runs – LIGENTEC can deliver small quantities of wafers with high performance, short turnaround times (two months), and devices sufficient for early stage proof of concept development as well as research programmes. Contact LIGENTEC for additional details: **www.ligentec.com**



Fast test needed for virus detection using integrated photonic biosensors

Shortly after Europe and North America joined many other global regions locking-down travel and banning non-essential activities in March due to the spread of the Novel Coronavirus (SARS CoV-2), EPIC (European Photonic Industry Consortium) held an on-line workshop focused on ways that PICs could play a key role in the development of faster, highly reliable contagious disease detection systems. Since that date, the COVID-19 infection has spread to millions while tragically killing hundreds of thousands of persons worldwide.

BY ANA GONZALEZ, R&D MANAGER AT EPIC

WHILE THE DISEASE has been arrested in some areas, infections continue to spike in others; fast, reliable and inexpensive testing remains a key tool in stopping the spread of the virus even as issues with existing, non-PIC-based, conventional tests remain in many countries including the Three As: Availability, Affordability and Accuracy. PIC Magazine invited EPIC to provide a summary of their workshop highlights and next steps that European photonic innovators are taking to enable faster disease diagnoses as well as related healthcare technologies. The current COVID-19 pandemic has demonstrated the urgent need to move from a laboratory-centred virus testing model to an approach based on low-cost, simple to use technology

Top: Figure 1: Testing of chips at wafer level. Courtesy of PIX4Life.

that enables rapid and reliable virus detection at homes and workplaces worldwide, particularly in developing countries. This article examines the present and future role of photonic integrated circuit (PIC) based biosensors as a key technology for a new generation of accurate, low cost and portable devices for the direct, real-time and label-free detection of viruses at a community level.

Currently, two types of virus detection tests are used in the COVID-19 pandemic: immunoassays tests that detect antibodies in the form of proteins associated with the virus and nucleic acid or molecular tests that detect the virus's genetic code.

Immunoassays

The presence of antibodies in blood indicates that a person is, or has been, infected by the virus. The test works on the same principle as a pregnancy test: the sample is applied on an absorbent area where it gets mixed with some previously deposited reagents and if antibodies are present, they are captured thereby indicating a positive result. While immunoassays are fast, portable, easy to use and can provide reliable evidence of a past infection, they are not sensitive enough to give a reliable diagnosis of a present infection.

Nucleic acid-based tests

These are the most sensitive in early detection of infection and have been widely used during the COVID-19 pandemic. They typically rely on a decades-old technique called reverse transcription polymerase chain reaction (RT-PCR).

A sample is taken by swabbing the nasal passages or throat which must then be sent to a laboratory for analysis on a costly PCR machine operated by specialist personnel. To find evidence of the virus, reagents and enzymes are added to the sample and any segments of the viral genetic code found are copied and amplified to make them easier to detect. While results can be provided in a couple of hours or less, when labs are inundated with samples, like at present, it can take anything up to 4 days.

Optical biosensors

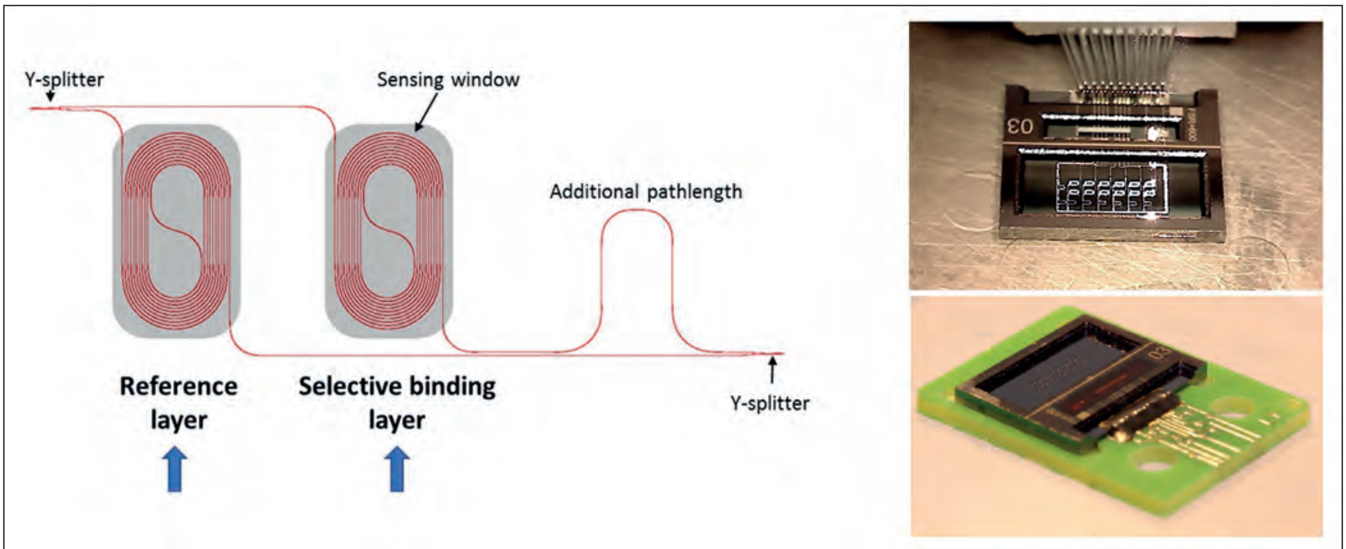
The current COVID-19 world health crisis has shown up the shortfalls and limitations of current laboratory-centred virus detection technology. PCR machines are large, costly and non-portable and in most cases require pre-treatment steps by skilled personnel before the sample can be introduced into the machine. These factors have combined to severely limit the number of tests performed and to create unacceptable delays in obtaining test results.

By 23 March, no country was able to test more than 3% of its population1 and by April 13th, apart from the US, no country had tested more than 1 million of its population2. Moreover, while the UK government set an optimistic target of 100,000 tests per day, it will take almost two years to test the whole population. (The UK set its original goal of 100,000 tests per day to be met by 30 April 2020.)

Photonic sensors could overcome drawbacks of current testing technologies and provide fast, affordable and cost-effective analysis. In recent years, optical biosensors have emerged as a particularly promising technology for the detection of a whole range of substances in a wide range of applications e.g., for health and environmental monitoring and the detection of microbial contaminants and toxins in the food industry. In the area of health monitoring, optical biosensors have been demonstrated as effective for the sensitive and selective detection of a wide range of analytes including viruses, toxins, drugs, antibodies, tumour biomarkers and tumour cells.

When the goal is to perform a test to an entire country population, mass-fabrication is key. PIC devices are a perfect candidate for being mass-produced at wafer level, becoming a cheap and disposable

Figure 2: Biosensor based on asymmetric Mach–Zehnder interferometers (AMZI). Bioreceptors such as antibodies are chemically linked on the sensing arm of the interferometer. Courtesy of LioniX International.



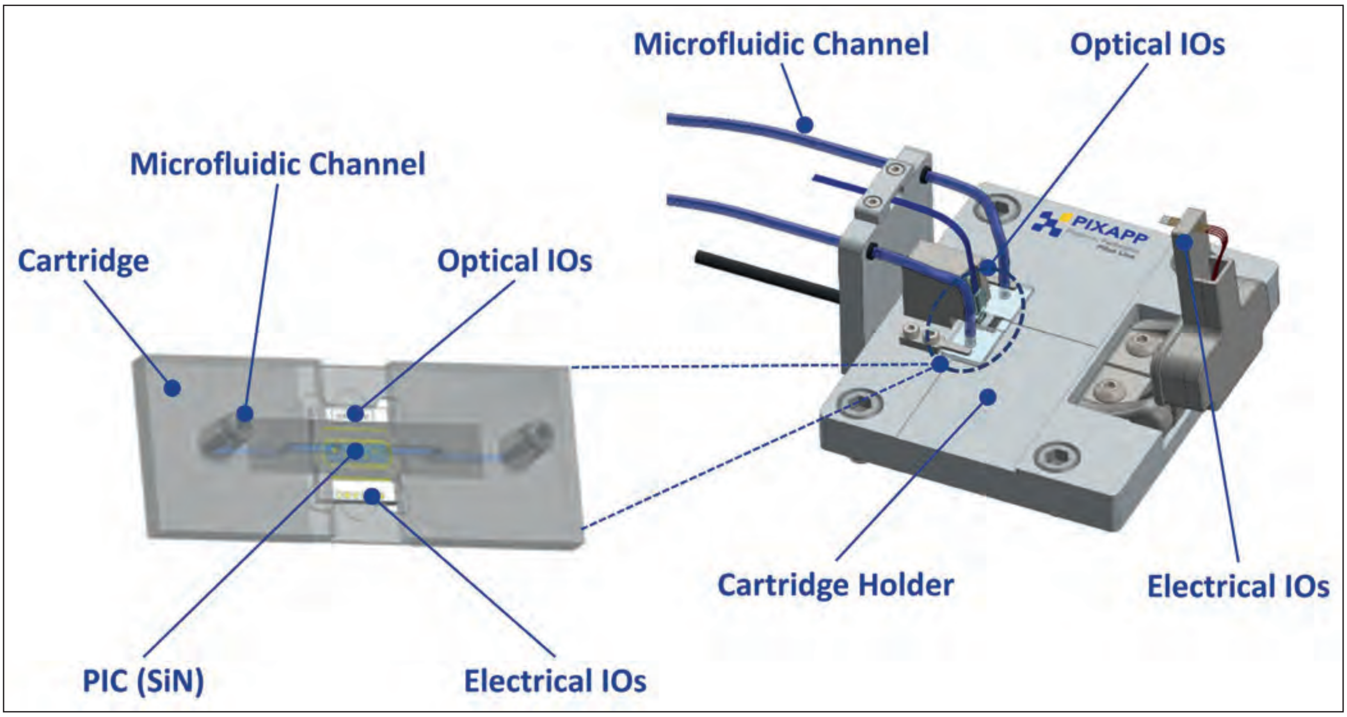


Figure 3: Final packaging for a biosensing chip designed for large volume production including microfluidics, optical coupling and I/O connections. Courtesy of PIXAPP.

technology suitable for biosensing applications. A PIC biosensor typically comprises a Si_3N_4 (Silicon Nitride) substrate containing three main types of integrated components: a waveguide with the sensing configuration such as ring resonators or interferometers and light coupling blocks (such as grating couplers), but also includes the microfluidics necessary to bring the sample to the sensor area of the device (see Figure 1).

In a typical PIC biosensor, a respiratory fluid or blood sample is allowed to flow over the functionalized surface of a sensor containing bioreceptors that have been specifically tuned to capture a particular antigen or antibody. Simultaneously, light in the VIS/NIR wavelength range is coupled into the PIC creating an evanescent field of a few nanometres over the sensor surface. When the target antigen or antibody is recognised, a change in the properties of the light (phase, frequency, or intensity) occurs, which can be correlated with the target concentration providing a real-time diagnosis.

Ideally, the design of the PIC takes into consideration the specifications of the target bio-application such as the minimum concentration of analyte that needs to be detected, the wavelengths of detection, and the packaging requirements such as the areas for attaching the microfluidics. Design houses, such as VLC Photonics, help companies in all the steps towards the development of a PIC-based device including the design of the photonic biosensing chips and selection of a foundry; they also support testing, packaging and ramping up to various production volumes.

There are different mature platforms that use PIC technology for biosensing. An example of a portable PIC-based biosensor device for virus detection was developed by Spanish company Lumensia in the

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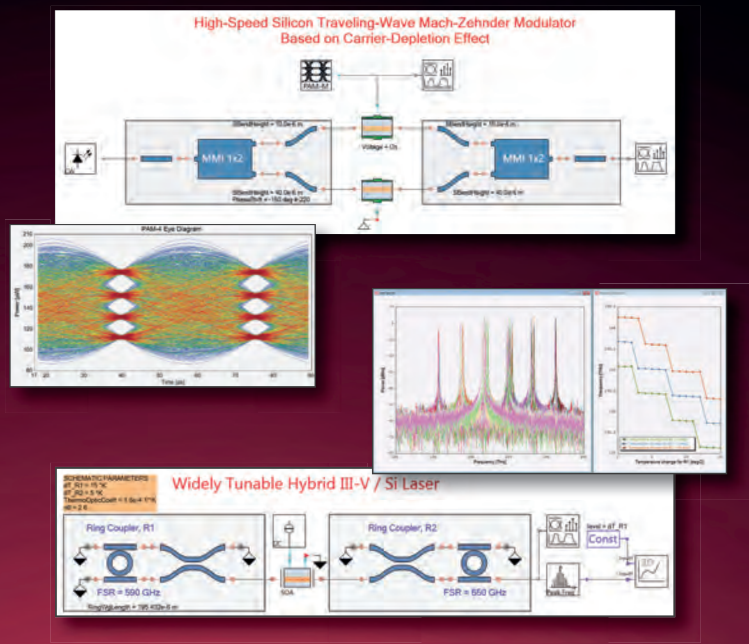

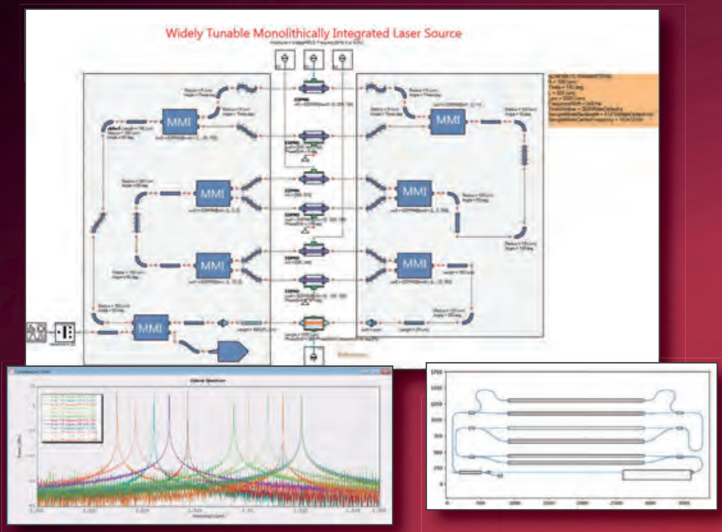

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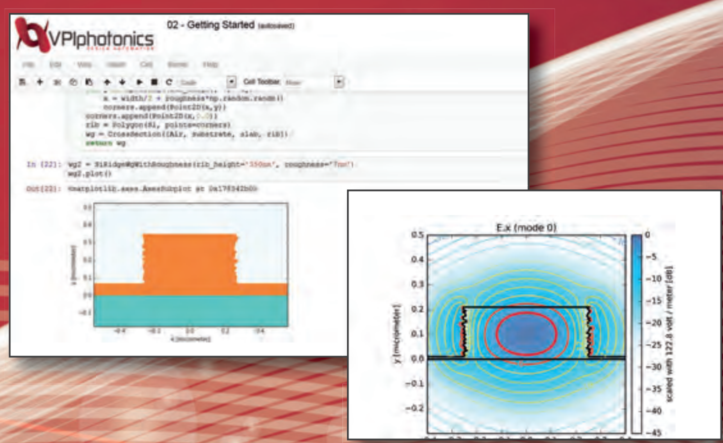
- Model bent waveguides and fibers made of dispersive isotropic and lossy materials



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framework of the H2020 funded project SWINOSTICS. Their prototype uses Si3N4 PIC sensors containing micro ring resonators to detect a range of viruses in pigs (e.g. African swine fever virus, Betaarterivirus, Influenza A, Porcine parvovirus, Porcine circovirus, Classical swine fever). Results can be provided in 10 minutes for mucus samples taken simultaneously, making it highly suitable for use in the field.

Moreover, LUMENSIA has recently also been awarded with a regional R&D project (Generalitat Valenciana, Spain) for the simultaneous detection of SARS-CoV-2 virus and its related antibodies IgG, IgM, IgA, leading for a diagnostics and pandemic tracking application that should be ready in six months.

Regarding COVID-19, a research team at the Catalan Institute of Nanotechnology coordinates the development of an optical biosensor (under the EU's Express Calls to tackle the coronavirus pandemic) to detect COVID-19 in humans as soon as it is present in the body. The detector is based on patented interferometric technology demonstrated at the open-access SiN platform of the CNM foundry, and comprises a bimodal waveguide interferometer, which uses two modes of light travelling in a single waveguide. Receptors on the sensor surface are specifically tuned to a certain antigen of the virus, and when the antigens are captured the light properties change indicating the presence of the virus in real-time.

LioniX International, a Dutch based vertically integrated foundry specialising in PIC production, is currently moving forward towards a commercial TriPleX platform to be used for COVID-19 virus detection. TriPleX is a Si3N4 platform that can accommodate various components in the form of building blocks to create different types of sensors, e.g. for optofluidic and fluorescent excitation sensing.

So far, research has shown that asymmetric Mach–Zehnder interferometers (AMZI) (see Figure 2) are better building blocks than ring resonators as AMZIs generate a much more sensitive sensor for detecting individual biomarkers. LioniX International is also collaborating with QURIN, a Dutch based company specialising in the use of LioniX's biophotonics sensor technology for early cancer detection.

Now, the goal is to move these technologies from a prototype stage to volume production, in which both the technology readiness level (TRL) and manufacturing readiness level (MRL) need to be increased from a prototype level of 4/5 to a level of 8/9 where the technology has been fully qualified and proven in a real operational environment and the capability for volume production has been demonstrated. In this context, the European Commission in a public-private partnership with Photonics21; it has funded a number of initiatives in the form of Pilot Lines with the specific aim of accelerating European technological and manufacturing readiness in respect of components and systems, also including PIC-based biosensor diagnostic devices.

These include MIRPHAB for the development of Mid-IR chemical sensors, JePPIX Pilot Line for production of indium-phosphide PICs; PIX4Life for production of Si3N4 chips for medical applications and PIXAPP for packaging and assembly solutions for PIC technologies. These Pilot Lines provide a service to companies based on standard processes designed to allow large-volume manufacturing. Considering COVID-19, PIXAPP and PIX4Life are currently working to develop a biosensor demonstrator that incorporates standardised packaging, alignment solutions to enable low cost and scalable optical packaging of optical biosensors suitable for virus detection (see Figure 3).

In a recent EPIC webinar on biosensors for virus detection3, representatives from these Pilot Lines explained how the projects were helping to accelerate PIC-based biosensor technology and to address the challenges for ramping up production with specific reference to COVID-19 testing.

Conclusion

PIC-based biosensor technology shows great promise for addressing the shortfalls and limitations of current laboratory-centred virus detection technology. However, in order to provide low-cost, point-of-care virus testing for communities worldwide, technological and manufacturing readiness needs to be accelerated to enable mass-volume production.

The European photonics pilot lines are making great efforts to address these challenges by fostering a strong unified ecosystem to ensure the adoption of design and manufacturing standards that will be required to ramp up production.

The existent robust ecosystem together with the increasing interest of the market for fast detection tools, provides the photonics industry with a unique opportunity to mass produce low-cost, portable PIC-based biosensor virus detectors to help fight this and future pandemics.

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PIC-Enabled CVD detector moves towards commercialization

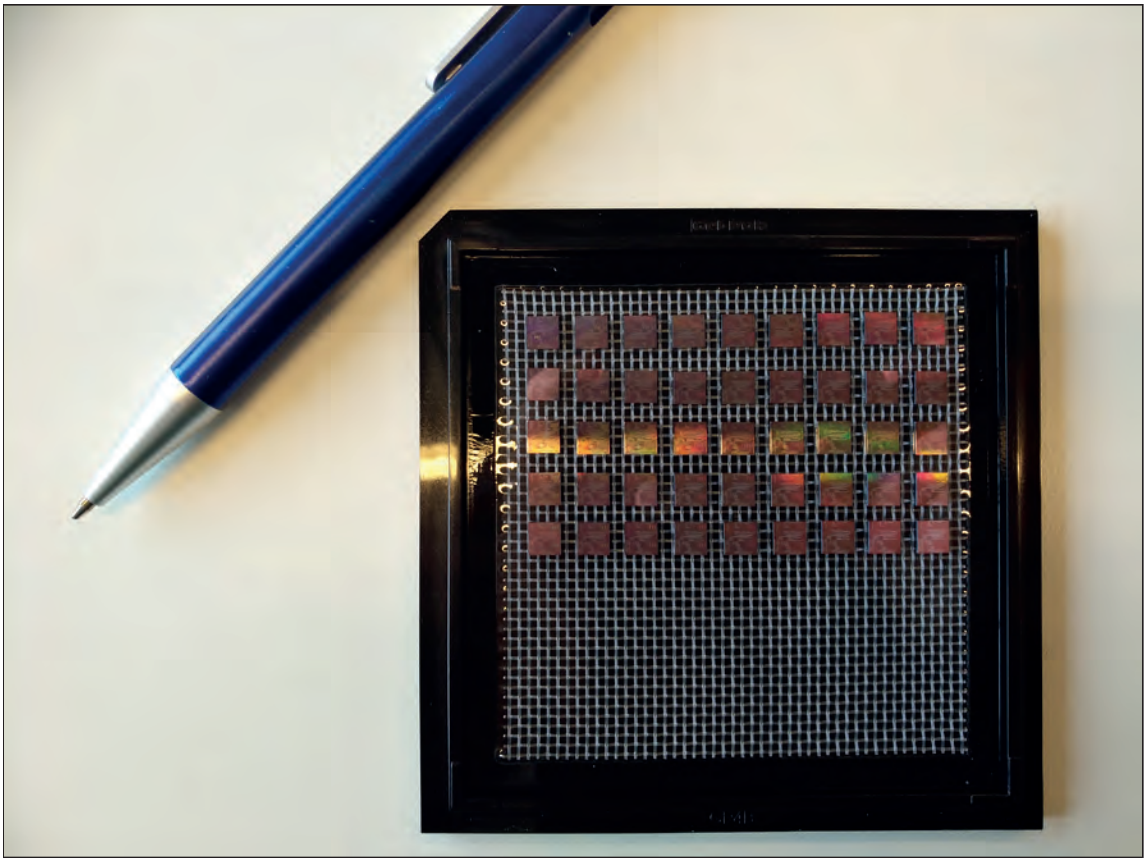
Cardiovascular disease (CVD) accounts for 30 percent of deaths worldwide each year. Although CVD is treatable under many circumstances, its diagnoses has up until now required skilled professionals and expensive, stationary medical tools. A partnership of EU-based researchers has used PIC technologies as key components for their new diagnostic tool that is making its way towards commercialization.

ONE OF THE MOST significant tools for medical diagnoses to come from the EU's H2020 programme is the portable, handheld CARDIS CVD detection tool that PIC Magazine first chronicled in 2019. Last year, the successful early clinical trials showed so much promise that researchers and their medical device manufacturer partners sought to move the device into final testing prior to its general release.

The prototype CARDIS medical diagnostic tool utilizes the principles of Laser Doppler Vibrometry on a patient's skin near major arteries to deduce metrics for arterial stiffness and to diagnose cardiovascular disease.

Imec, a leader in nanoelectronics research and innovation hub, together with Medtronic and other project partners recently announced that the CARDIS project was entering its next stage under auspices of the H2020 InSiDe project. The objective of InSiDe is to provide access for the medical community to CARDIS—a mobile CVD diagnostic device based on silicon photonics that is designed to identify and characterize different stages of cardiovascular diseases. The device offers fast, flexible and patient-friendly monitoring, which is expected to allow many if not most patients to remain in their home environments while still being able to monitor their hearts—easier, non-invasive and inexpensive access is expected to enable productive follow-up care and intervention as a patient's condition requires.

"The InSiDe project has been triggered by the remarkable outcome of the H2020 project CARDIS. Together with CARDIS project partners, we developed a prototype mobile, affordable, point-of-care screening device for CVD. The device enables fast and reliable measurement of CVD-related biophysical signals through minimal physical contact with the patient and minimal skills from the operator," stated Prof. Dr. Roel Baets, group leader at imec and professor at Ghent University. "The objective of the InSiDe project is to take this CARDIS prototype device a major step further towards proven medical relevance and towards commercialization." Bates noted that the CARDIS device has already successfully been utilized in previous clinical trials including its initial public



Silicon photonic chips are key to realizing the handheld CARDIS device for measuring arterial stiffness

feasibility study with 100 patients at the Georges Pompidou European Hospital in Paris.

The CARDIS point-of-care device operates based upon the principles of Laser Doppler Vibrometry (LDV). In LDV, a low-power laser is directed towards the skin overlying an artery; the skin's vibration amplitude and frequency, resulting from the heartbeat, are ascertained from the Doppler shift of the reflected beam. The key underlying technology is silicon photonics (SiP), which allows the implementation of advanced optical functionality in a chip produced in an industry-standard CMOS fab. After prototype devices successfully completed its initial clinical feasibility study in Paris, the device underwent additional testing at the Academic Hospital of Maastricht (The Netherlands), collecting a substantial clinical dataset from both healthy subjects as well as from patients with cardiovascular conditions.

The quality of the device readings was found to be very good and adequate biophysical signals could be obtained in all subjects. The researchers have indicated that although the data collected to date has been clinically relevant and accurate, further work is needed to facilitate the algorithmic translation to relevant markers for medical pathologies. "The very promising results from the CARDIS project stimulated the consortium to take the next step and aim at bringing the prototype to a truly manufacturable product that is useful for (general practitioners) and cardiologists in their daily practice."

According to Bates and imec spokespersons, the InSiDe project has the following primary objectives designed to advance the CARDIS prototype device towards commercialization:

- Develop a true handheld clinical, battery-operated investigational device capable of measuring, quantifying and recording cardiovascular conditions;
- Develop algorithms to translate the interferometer signals into data that are relevant to monitor and diagnose a number of cardiovascular diseases (CVDs);
- Demonstrate in clinical feasibility studies the usefulness of the device for GPs and cardiologists;
- Outline a path to industrialization and manufacturability.

InSiDe is supported by the European Union's Horizon 2020 Framework Programme for Industrial leadership in Information and Communication Technologies (H2020) and by the Photonics Public Private Partnership Photonics21. Over the next four years, InSiDe will be managed by imec through the organization's associated laboratory located at Ghent University: the Photonics Research Group in the Department of Information Technology). The Medtronic Bakken Research Center (Netherlands) will be responsible for the scientific and technical coordination of the project. Other industrial, academic and clinical partners will bring their expertise to the project including: Ghent University (Belgium), Politecnico di Torino (Italy), Tyndall National Institute

(Ireland), Microchip Technology (United Kingdom), Argotech (Czech Republic), the National Institute for Health and Medical Research – INSERM (France), Universiteit Maastricht (Netherlands) and Fundico (Belgium).

Roel Baets, project coordinator from imec/UGhent, was scheduled to present the results of the CARDIS project and the aims of the InSiDe project on 3 February 2020 at ITF Photonics, an industry event co-organized with SPIE BIOS and SPIE Photonics West by imec and SPIE.

CARDIS leverages compact, cost-effective silicon photonics

The CARDIS prototype device makes use of multi-beam Laser Doppler Vibrometry (LDV), whereby a set of low-power laser beams are shone onto the skin above the carotid artery of the patient. The power level is so low (well below 1 mW) that it is completely harmless to the eye and skin. The reflected light is Doppler shifted in optical frequency due to the tiny movements of the skin above the artery as a result of the heartbeat. By doing measurements at multiple locations, the pulse wave velocity (PWV) can be deduced. The new CARDIS device is very compact because reliance on SiP devices for the basic LDV engine, allowing the hardware to be miniaturized to a handheld device.

The photonic chips at the heart of the CARDIS system have been designed and manufactured at imec using its silicon photonics iSiPP50G process – including passive functions, modulation and switch functions as well as germanium detectors. The chip is co-assembled with a micro-optic bench holding a 1550nm single mode laser, a miniature optical isolator and coupling structures to the chip. The packaging of the photonic chip was executed at Tyndall National Institute (Cork, Ireland).

Imec's Silicon Photonics Platform co-integrates a wide variety of passive and active components, thus enabling competitive photonic integrated circuits for a broad range of functionalities and markets – including data centers, telecom, sensors, LIDAR, etc.

As demonstrated in the CARDIS use-case, silicon photonics makes a huge difference when a device needs to be miniaturized to the extreme, or when the device – such as a point-of-care device – needs to be optimized with respect to cost and also when reliable manufacturing and/or large volume production is needed.

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 871547.

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New opportunities for collaboration within the photonic packaging supply chain

Photonic integrated circuits (PICs) have enormous potential to reduce the size of myriad Tx/Rx high data rate components and are already seeing increased use as sensors, within Industry 4.0 systems and in many other applications. Automating test, assembly and packaging (TAP) remains a requirement for widespread PIC adoption. EPIC provides new insights into ways EU-based companies are bringing solutions to market.

BY ANA GONZÁLEZ, R&D MANAGER AT EPIC

PACKAGING AND TESTING of photonic devices have been considered the main bottleneck to overcome for the mass-production of photonic based products. Passive/active optical alignment, wafer-level vs. die level packaging and testing, thermal considerations and volume vs. price considerations are still hot topics, widely discussed by the photonics industry.

This article aims to give insights about the interests and needs of companies along the entire supply chain in photonic packaging. It also summarizes the latest developments and advances directed to scale-up photonic packages in a sustainable way together with the state-of-the-art of the current technology, highlighting companies and the different solutions proposed. The increasing demand for new technologies able to provide fast and direct diagnostic tools, highly accurate position sensors, and faster / more secure communications has triggered interest in the development of products based on photonics. When developing a photonic product, the packaging of the final module must be considered in the initial design, as it will considerably impact the final price of the device. Furthermore, to satisfy the needs of mass markets such as communications and automotive, the packaging processes employed in the production of photonics devices must be scalable and cost-effective, which requires a collaborative effort between all levels of the supply chain.

This article will explore the steps needed to package a photonic chip, with special focus on the capabilities of the key companies in the packaging supply chain in photonics, highlighting their needs and the corresponding connections between the different levels.

Software, Design, PIC foundries, and Prototyping Photonic structures can be accurately simulated using a wide variety of software platforms provided by companies such as VPI Photonics, Luceda Photonics, Synopsys, Lumerical and Mentor, a Siemens Business. However, to speed up the design and optimization process, it is possible to use the services provided by design houses such as Bright Photonics that can develop customized PIC circuit designs using foundry compatible mask layout for manufacturing.

The materials for the fabrication of the chip are chosen following the requirements of the application. There are several foundries working with different technologies such as InP PICs (Smart Photonics, Fraunhofer HHI, III-V labs and CST Global), Silicon photonics and Silicon Nitride (imec, CNM, LIGENTEC, LioniX International and Compoundtek). Many of these foundries are offering multi project wafer (MPW) runs, which allows users to start with a specific design by getting a few chips from a wafer which is shared between different customers reducing considerably the costs of producing the first chips.

However, for users requiring InP chips with higher TRLs, JePPIX Pilot Line offers the commercial fabrication service of full wafer runs, for customer designs at TRL 7, enabled by a set of target performance metrics, which include foundry-specific manufacturing tolerances in the PDKs. CST Global also offers other materials such as InGaAs and AlInGaAs, while Enablence offers polymer planar lightwave circuits. Remarkably, the combination of Si and InP in a single chip is being industrialized by SCINTIL Photonics.

Once the first optical chips have been fabricated, the devices can be packaged, and it is often useful to have a research partner who can adapt the packaging processes to the application. An example of such a partner is VTT, which offers expert services from designer prototyping to manufacturing. They have unique and tailored research and innovation services, with wide technology and IP, as well as extensive research facilities both in-house and together with partners. VTT develops a variety of photonics integration and packaging technologies, from module packaging with fibre-optic modules that include high precision photonics assembly.

They have a large experience in ceramics interposers in photonics packaging, particularly in applying multi-layer ceramics in advanced photonics and packaging. The advantages include applicability to extremely high frequencies, which in photonics, enables miniaturized packaging of fibre optic transceivers, sensors, and a system-on-package approach. They are part of the PIXAPP consortium, where they provide this ceramic packaging approach for extremely high frequency PIC applications. VTT also participates in the H2020 PASSION Project, which provides a disrupting technology for metro-networks, assuring a transmission rate of over 100 Tb/s per link and a switching capacity of over 1 Pb/s per node, in which VTT is working on integrating VCSELs directly on SiP waveguides thought mirror coupling.

Packaging and Assembly

Once the prototyping phase has proved successful, thereby validating the optical packages, the design and chip fabrication, it is time to find scalable packaging processes with a focus on the automation of processes to reduce the cost of the final package. For this, there are companies offering different packaging solutions e.g., as offered by PHIX Photonics Assembly, Boschman, member companies of the Torbay Hi Tech Cluster (located

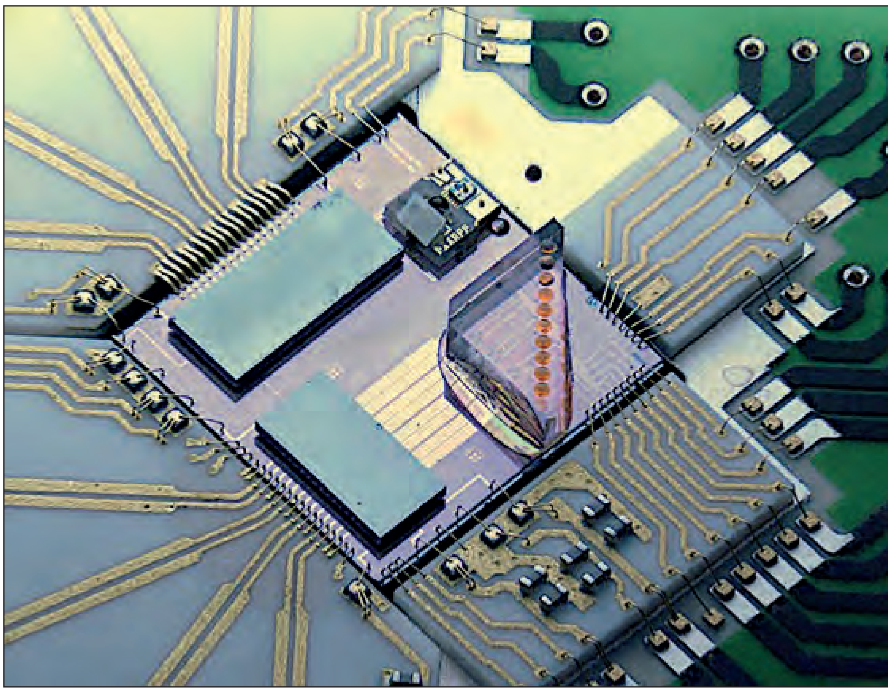

Figure 1. Building blocks offered by PIXAPP Pilot Line to the companies for standardized packaging. Courtesy of PIXAPP.

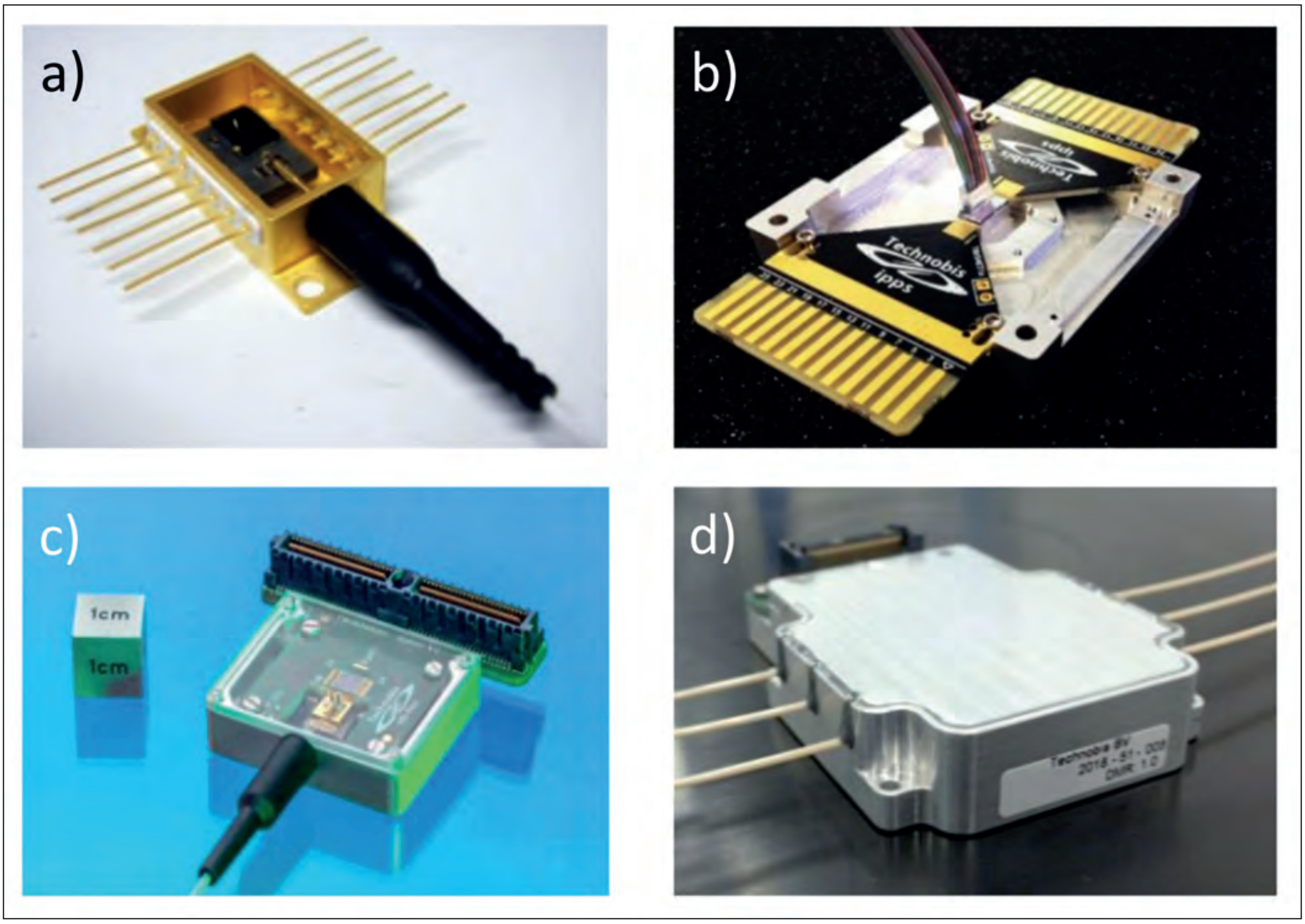

Figure 2. Different standard packages offered by Technobis: a) generic butterfly packages, b) RF package, c) fibre sensing package for temperature sensing, and d) fibre sensing package for landing gear load monitoring on aircraft. Courtesy of Technobis.

in the Electronics & Photonics Innovation Centre, EPIC) and Linkra. Other companies such as SQS Vlaknova Optika specialize in fibre optics assemblies and optoelectronics. AEMtec offers opto-electronic packaging and AFE offers fibre alignment services, while Nanoscribe offers two-photon polymerization processes that can be used to fabricate micro lenses arrays for coupling light in PICs.

For companies that want to speed up the packaging phase, there are initiatives that can offer all processes that are needed for the packaging in a single gateway, assuring that these processes are compatible, such as the Pilot Lines in Photonics programme. Set up in 2017, PIXAPP (PIC Assembly and Packaging Pilot Line) is a European initiative to bridge the 'valley of death' often associated with high-tech SMEs moving from prototyping to low-volume fabrication. To this end, PIXAPP gives companies an easy-access route to transferring R&D results to the market, thus enabling them to exploit the breakthrough advantages of PIC technologies.

The aim is to develop a packaging process that can be scaled up and transferred to industrial partners. To facilitate this, PIXAPP provides a series of building blocks comprising standard processes that can be transferred to standard package formats (see Figure 1). For its next phase as a legal entity, PIXAPP is looking for new partners able to complete the Pilot Line offer at a global level.

There are also different companies that offer a range of processes such as First Sensor. They offer a range of both custom and off-the-shelf sensors, including pressure sensors, flow sensors, inertial sensors, and various optical sensors with a focus on the industrial automotive and medical markets. They provide 4 core technologies: 1) 2-12-inch wafer dicing; 2) die bonding, organic FFO materials and metal; 3) highly accurate dye placements; 4) aluminium and gold wire bonding. Their target customers are companies who want to build custom specific test equipment to utilize for the end test.

One of the biggest success stories of PIC product development in Europe is Technobis, a PIC packaging company providing production and test facilities for prototyping and small series production for universities and start-up companies with a focus on the aerospace, space, medical and automotive sectors. They can perform processes for fibre array alignment, advanced fibres, wire bonding, die bonding, oven curing and thermal management. They can also do prototyping and small series production, and they are now increasing their capabilities for volume production including automatic fibre alignment for welding and bonding, as well as bonding for automatic fibre array alignment.

Furthermore, they are PIXAPP partners, so they follow the packaging rules of PIXAPP, and develop compatible processes. Technobis also commercializes generic test packages such as: 1) generic butterfly packages (see Figure 2a); 2) RF package designed for fast testing of chips with RF connections and high/low density DC (see Figure 2b); 3) the fiber sensing package, that contains six light sources and around 2,000 sensors in one fibre; it is used in an aircraft for temperature sensing (see Figure 2c); and 4) a package with dual analogue sensing systems inside, comprising cooling pillars, six interrogators and three light sources used for landing gear load monitoring on aircraft (see Figure 2d). They would benefit from faster tools for faster alignment.

Testing

When ramping up production of photonics products, there is a process that is becoming increasingly relevant: the testing of a huge number of devices after the different production steps. There are companies already active in this area who offer services for chip testing at bare/die/wafer level. However, investment is still needed in this field to be able to cover the future needs of the industry.

But there are companies moving in the right direction. VLC photonics provides engineering services for the development of photonic integrated circuits including in-house design, characterisation, testing, manufacturing, and packaging through their network of partners. They provide characterization services at die level, and packaging testing. They are also developing capabilities for wafer level testing for optical and electrical measurements. They are currently looking for partners to develop new equipment for flexible but also very customized testing, such as for RF probes and a backup of RF proof, and for fibre array coupling. They are also looking for equipment able to manage different types of coupling, e.g., lens fibres and fibre arrays.

Regarding automation and parallel channels, Jenoptik Optical Systems offers optical solutions for high volume testing of PICs on wafer level to satisfy this aspect of market demand. Their solution is based on a standard prober interface with a monolithic optical module to form a glass-based optical device with passive optical circuitries and waveguide assembly. The current prototype has 16 optical channels (I/Os) which are completely integrated into the probe card, does not need active alignment nor skilled personnel to operate, and allows parallel measurements. Developments in the near future will allow more parallel measurements and they are looking for companies able to perform PIC testing such as VLC.

Automation equipment

After the pre-commercialization phase is complete and the devices have been shown to meet the specifications, it is time to think about going to commercial production. This will require an important investment in automation tools for ramping up production to the number of devices required. Companies such as Vanguard, Nanoscribe, Aerotech, Aifotec, AMICRA and Aixemtec are developing different automation equipment including laser soldering, lenses alignment, flip-chip, adhesive bonding and all other processes needed to package a photonic chip.

In this growing market, one of the leading companies is FiconTEC, which develops machines for automated micro-assembly and testing of photonics systems and devices. They currently provide machines for passive and active devices, laser soldering processes, epoxy attached processes of laser chips. Their main area is the reactive attachment and alignment of lenses and optical subassemblies, including fibre array and fibre-attached processes. FiconTEC provides robust, fast, and reliable technology for specific processes.

However, if you are looking for reconfigurability and flexibility, Aixemtec provides machines and components for precision assembly and testing using a flexible machine platform in which different process plates can be introduced. The system can be reconfigured in a short time, which is a valuable capability as it enables a quick ramp up for new processes, e.g., tools for super precise dispensing routines and micro-optics handling. Another key advantage is that the same machine can be used for different processes, e.g., fibre assembly for fibres or optics assembly and for different kinds of systems, like laser projecting and imaging systems.

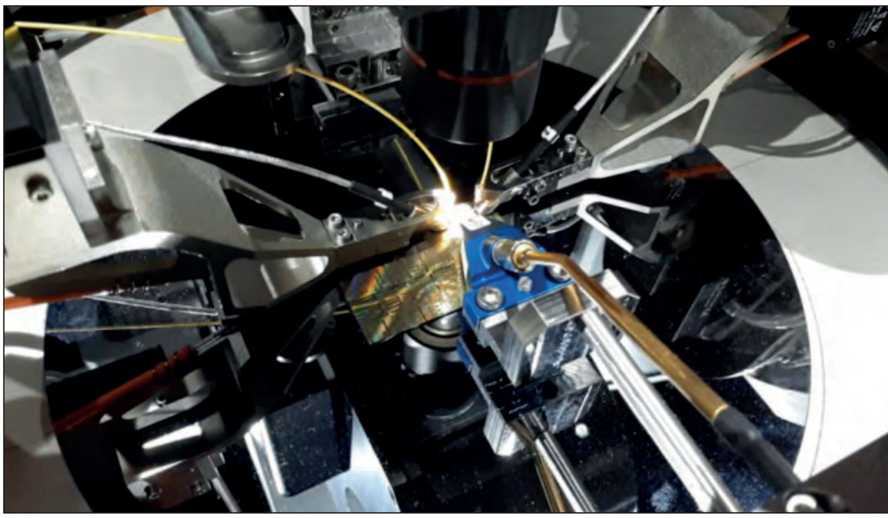

Figure 3. Detail of an alignment system using PI nanopositioners technology. Courtesy of PI.

If you are exploring bonding processes, the best option is Finetech. They develop and produce advanced micro assembly systems, mainly submicron bonding systems for photonics packaging, as well as advanced systems for high-end applications, such as mini LEDs. They offer adhesive bonding, including UV soldering and nano foil. For laser bars, they have several compressions and laser assisted bonding processes for active alignment. They also have expertise in placing lenses for passive alignment.

When looking inside an automation machine, there is a high probability of finding Physik Instrumente (PI) nanopositioners. PI is a leading manufacturer of nano-positioning technology. They facilitate highly accurate placement by means of their parallel alignment technology that allows alignments across multiple inputs and outputs as well as elements and channels and degrees of freedom that can all be done in one step.

Instead of time-consuming repetitive alignments, PI's technology allows all to proceed in parallel, so instead of alignment taking place in minutes, it is achieved in typically less than a second. Used in combination with other sub systems, the PI approach offers nine degrees of freedom for motion purposes and enables the coupling of fibres and arrays to PICs and SiP structures (see Figure 3).

Conclusion

The development of novel and exciting applications for photonics is creating a new generation of products in markets such as optical communications, medical and automotive, and a demand for the processes and tools to enable the mass-production of these devices. In this article, we show that while Europe has a strong supply chain for packaging and assembly of photonic devices, there are still some challenges to overcome such as the need for faster alignment tools and effective processes for testing at wafer level. These and other topics will be discussed at the EPIC Meeting on Automation for Manufacturing (Packaging and Testing) at PI, 29-30 October 2020, in Karlsruhe, Germany. This meeting will focus on the main markets needing volume production, namely optical communications and automotive, and the latest advances in photonics packaging such as the co-packaged optics for Ethernet switches.

For more details, visit the website https://www.epic-assoc.com/epic-meeting-on-automation-for-manufacturing-packaging-and-testing-at-pi

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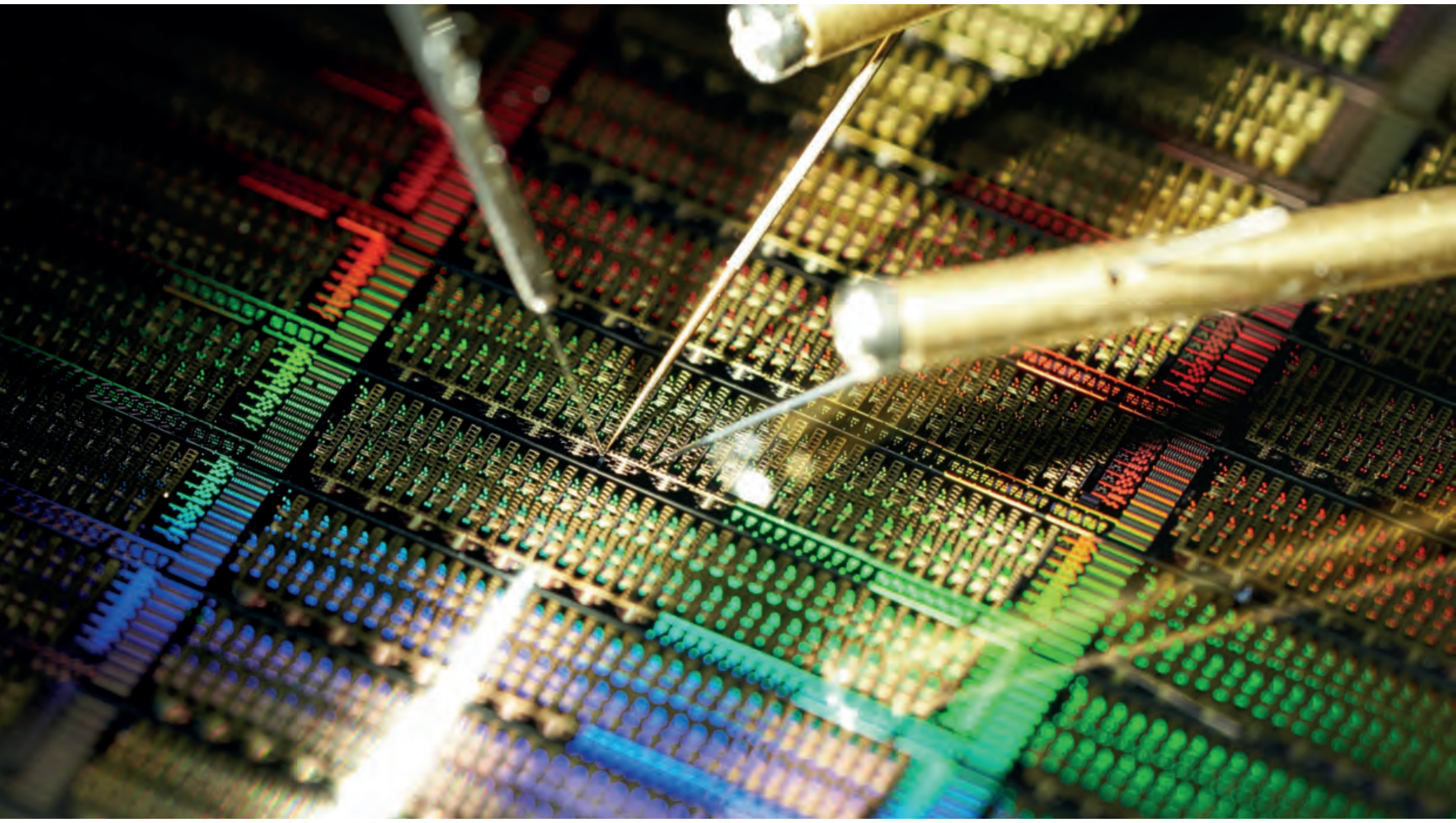

Comb lasers advance high-performance computers

By tackling a bottleneck in bandwidth, multi-wavelength quantum dot lasers are enabling improvements in high-performance computers

BY GEZA KURCZVEIL, DI LIANG AND RAY BEAUSOLEIL FROM HEWLETT PACKARD ENTERPRISE

GROWTH IN DATA is occurring at a phenomenal rate. Now it takes just two years to produce 90 percent of all the data on the internet. That has major implications, particularly as it comes at a time when the performance of single cores has stagnated (see Figure 1 (a)).

To make headway, efforts are no longer directed at trying to increase the clock speed of single cores, but are focused on the construction of processors with more and more interconnected cores, and limited private memory on one socket. This new architecture makes much sense, given that memory is cheap, the opposite of what it was when the first computers were being built. In future, high-performance computers will feature a massive pool of memory at the centre, surrounded by many compute nodes located at the periphery, with all nodes having access to the full memory pool (see Figure 1 (b)).

A key requirement for this new high-performance computer architecture is a massive communication link for the massive pool of memory. Without this, there would be insufficient throughput of data between memory and compute nodes.

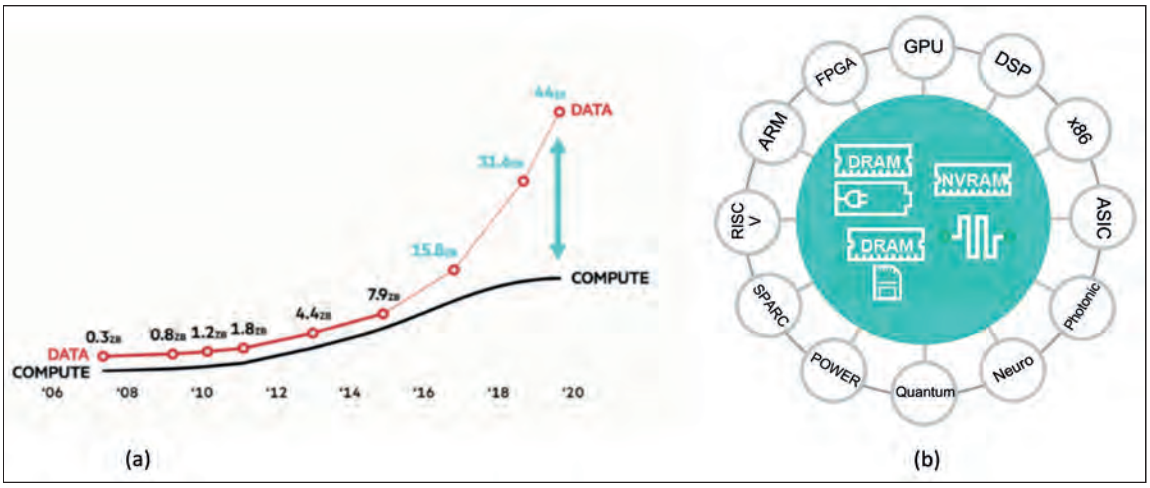

Figure 1. (a) While memory has gotten cheaper over time and there has been an exponential rise in the generation of data, single-thread performance has stagnated. (b) In memory-driven computing a massive pool of memory is at the centre of the architecture, and application-specific compute nodes are placed at the periphery. Each compute node has access to the full memory pool.

One option for the data link is electronic interconnects, such as copper wires. However, they suffer from significant losses, high power consumption, and cross-talk at higher frequencies. A far better alternative is optical interconnects, which address all the weaknesses of wires while allowing the transmission of multiple wavelengths. Data can be transmitted through these links using a technology known as wavelength division multiplexing, which avoids any crosstalk between channels. It is a well-established approach for routing internet traffic when distances and bandwidths are large enough to justify the cost – and as deployment has increased, prices have fallen, making these links common-place in applications where distances are on the order of just a metre. As that's a length scale found in high-performance computing, optical links are already used for rack-to-rack connections.

High-performance computers require aggregated data rates of terabits per second. Today, this rate is out of the reach of a single laser, so the aggregated data rate is sliced up between many lasers, each making an equal contribution. Although individual lasers can transmit at above 200 Gbit/s, data rates of only up to 20 Gbit/s are actually used, to minimise energy consumption.

A common approach for operating these lasers is amplitude modulation. But this has a downside, producing sidebands above and below the original optical carrier wavelength (see Figure 1 (c)). Due to this, the sidebands of one channel have to be sufficiently separated from those of the neighbouring channels to minimise crosstalk. When driving a laser with amplitude modulation at a data rate of 50 Gbit/s,

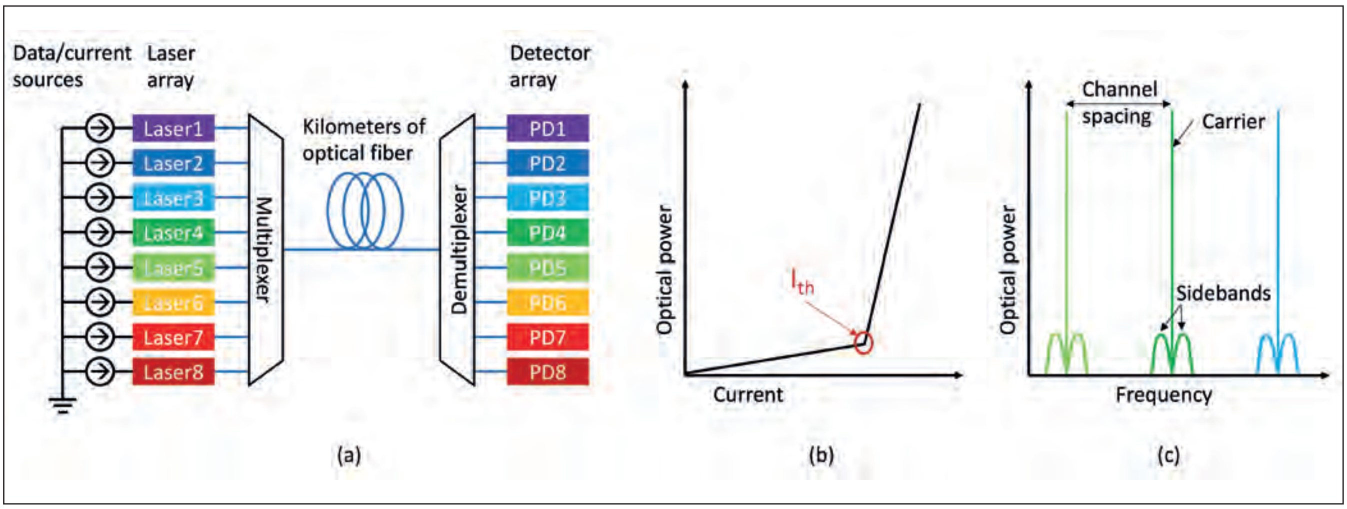

Figure 2. (a) A typical optical link consisting of several single-wavelength lasers. Data are encoded on the optical signal by turning each laser on and off. (b) The output power of a laser as a function of injection current. Once data are encoded onto a laser signal, sidebands are generated. As long as the sidebands of neighbouring channels do not overlap, there is no crosstalk between channels. This is accomplished by limiting the modulation speed.

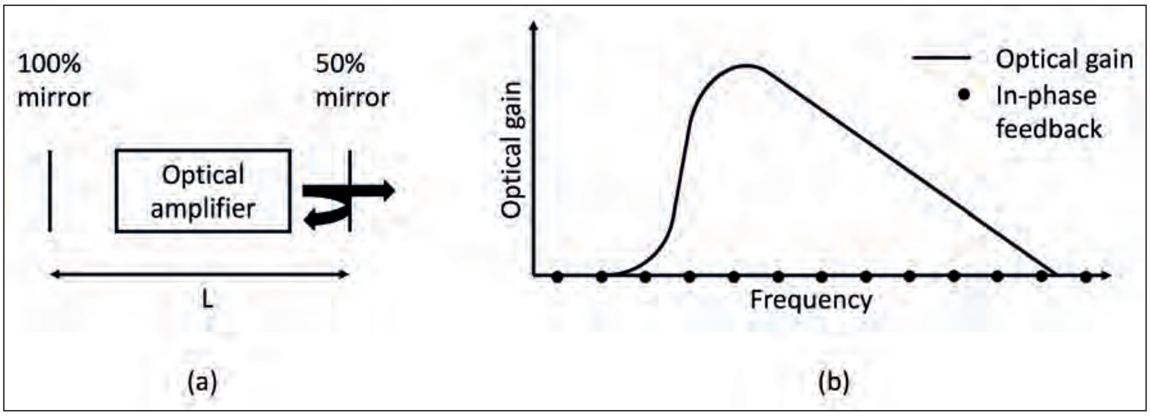

Figure 3. (a) A basic laser cavity contains an optical gain amplifier, surrounded by a pair of mirrors. (b) Lasing occurs at frequencies where light experiences a positive net gain and the feedback from the mirrors is in phase with the light in the cavity.

there needs to be a 3.5 THz channel spacing to minimise crosstalk.

To transmit data using wavelength-division multiplexing, signals from a number of lasers are united by an optical multiplexer, routed through a fibre, and sent to a demultiplexer that returns the data back to a collection of signals at different wavelengths. Photodetectors then convert all of these signals into electrical signals, which is the form required by today's processors and memory. Note that this scheme, which works very well, is particularly attractive for links with low-to-medium volumes of traffic, because it allows unused channels to be turned off, saving power.

Unfortunately, wavelength-division multiplexing is not easy. There are often imperfections in the laser production process, resulting in variations in the lasing wavelength. Addressing this requires active monitoring and tuning. If there are many channels, and the spacing is below 100 GHz – this is the case in dense wavelength division multiplexing – variations in wavelength can create significant problems. In such situations, rather than using many single-wavelength lasers, it is better to use one laser that provide multiple wavelengths – a comb laser.

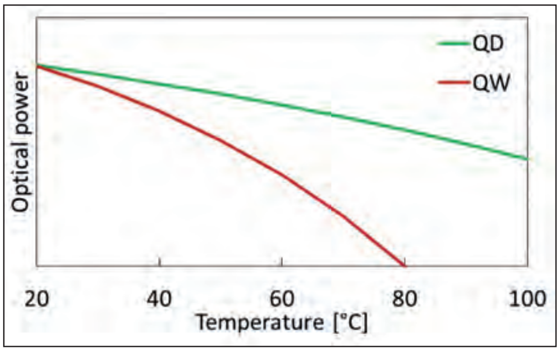

Figure 4. As the temperature of the laser junction increases, optical output power decreases. Due to the three-dimensional confinement of electrical carriers, the power drop in quantum-dot lasers is far smaller than in traditional quantum-well lasers. This makes quantum-dot lasers especially attractive for applications where temperature control is impossible or limited.

Comb credentials

A key difference between a conventional, single-wavelength laser and that with a multiple wavelength comb is the reflectivity of the mirrors. Conventional lasers need an additional bandpass filter inside the cavity – or at least a narrow-band mirror – to ensure single-wavelength lasing, while comb lasers employ a more straightforward design, tending to consist of a long cavity and broadband mirrors (see Figure 3(a)). For cleaved lasers, which can be formed with cleaved facets, the cavity can be 0.5 mm or longer, depending on the desired channel spacing.

With a comb laser, the spacing between the lines is fixed. Although changes in temperature shift the entire comb to either higher or lower wavelengths, once one knows the wavelength of one of the comb lines, one knows the wavelengths of them all. That's because the channel spacing is determined lithographically, and it is therefore a prescribed, controllable design parameter.

Given the great simplicity of the design of the comb laser, one may wonder why anyone would ever go to the trouble of making a single-wavelength laser. The reason is that when a comb laser is built with the most commonly used optical gain medium – a stack of quantum wells – this device is impaired by an intrinsic material property known as mode partition noise. This impediment produces random fluctuations in optical power for every comb line. Although these fluctuations, occurring on a nano-second timescale, do not alter the total optical power, they are a show-stopper for error-free data transmission. That's because it is not possible to transmit an optical 'one' while the power of a comb line has randomly dropped to zero.

So why have comb lasers suddenly risen in popularity, given these issues? Ironically, the recent success has nothing to do with comb lasers. Instead, progress has been driven by the development of a relatively new gain medium, quantum dots. Researchers in Japan pioneered these low-dimensional structures, developing a laser with greater tolerance to temperature variations. By switching from wells to dots they were able to increase the confinement of electrical carriers, with early experimental work verifying an increase in high-temperature gain stability lumerical

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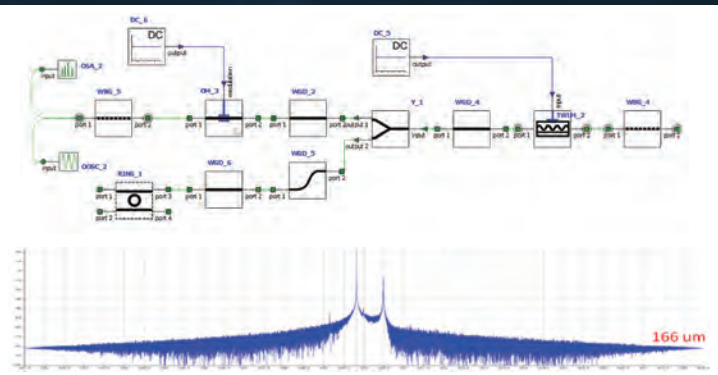

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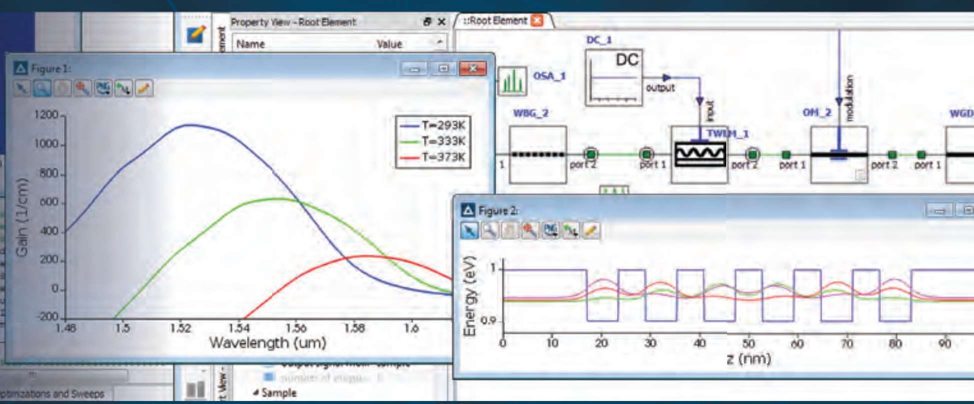

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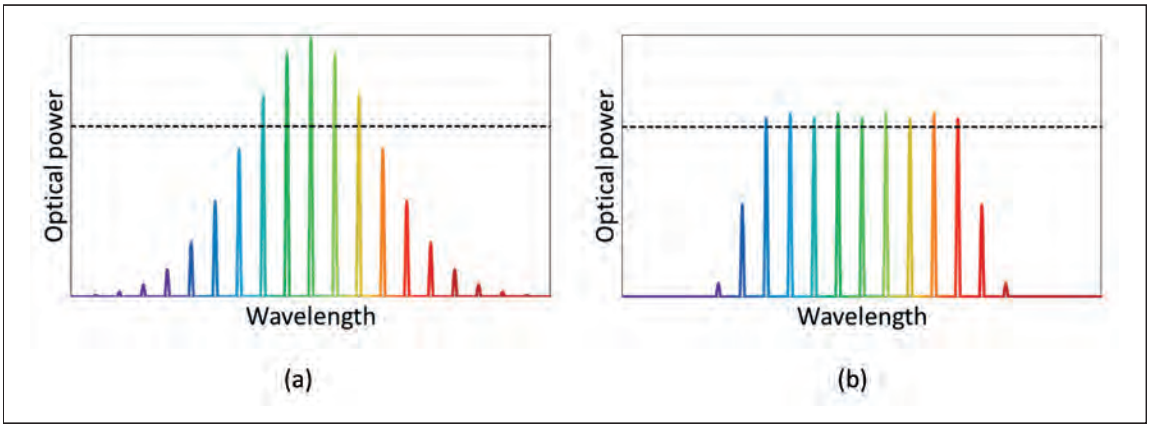


Figure 5. (a) Some comb lasers exhibit a Gaussian distribution of amplitudes. The dashed line indicates a hypothetical power level for noise-free data transmission. Comb lines with less power cannot be used, so they reduce the device efficiency. (b) Quantum-dot-based comb lasers produce a more rectangular optical spectrum. This device has the same total power as the one in (a). Note that more channels satisfy the power requirement for noise-free data transmission.

(see Figure 4). After this success, it took a few more years until a collaboration between researchers in Germany and Russia investigated the topic of mode partition noise in quantum dot comb lasers. This work revealed that the introduction of dots quashed the partition noise in these devices.

Not all comb lasers are created equally. Some are more practical than others for data communication, because they combine a low mode partition noise with a flat comb that ensures that all channels have similar signal-to-noise ratios. Poor candidates for high-performance computing include lasers with frequency combs generated in SiN resonators, as they show a Gaussian distribution of comb line amplitudes (see Figure 5 (a)). The good news, for reason yet to be understood, is that the combs from quantum-dot lasers produce flat spectra with a relatively uniform power over a large number of comb lines (see Figure 5 (b)). However, not all comb lasers are suitable, as there are problems with pulsed variants (for details see the box "The problems of pulsed comb lasers").
Encoding independent data streams on each comb line is not as straightforward as for a single-wavelength laser. Turning the laser on and off by modulating its injection current encodes the same data stream on all the comb lines, which is inefficient.

Instead, our team at Hewlett Packard Enterprise has the comb laser on at all times (see Figure 6) and places several micro-ring modulators outside of the laser – we have one for each comb line (see Figure 7 (a)). This approach exploits a key characteristics of micro-ring modulators, a wavelength dependent loss (see Figure 7 (b)). By adjusting the voltage of the *p-n* junction of the micro-ring, we shift the wavelength of maximum loss, which is the resonance wavelength. To generate an optical 'one', we tune the resonance wavelength away from the comb line; and to produce a 'zero', we line-up the resonance wavelength with the comb line.

Our micro-ring modulators are compact, with a diameter of around 10 μm. With proper design, they can transmit data at 50 Gbit/s. The full-width-half-maximum of the micro-ring's resonance is ideal, being wide enough to capture an entire comb line, but narrow enough to allow neighbouring comb lines to be transmitted without any loss in optical power. Selecting the resonance wavelength of the micro-ring is relatively easy, as it can be tuned by adjusting the

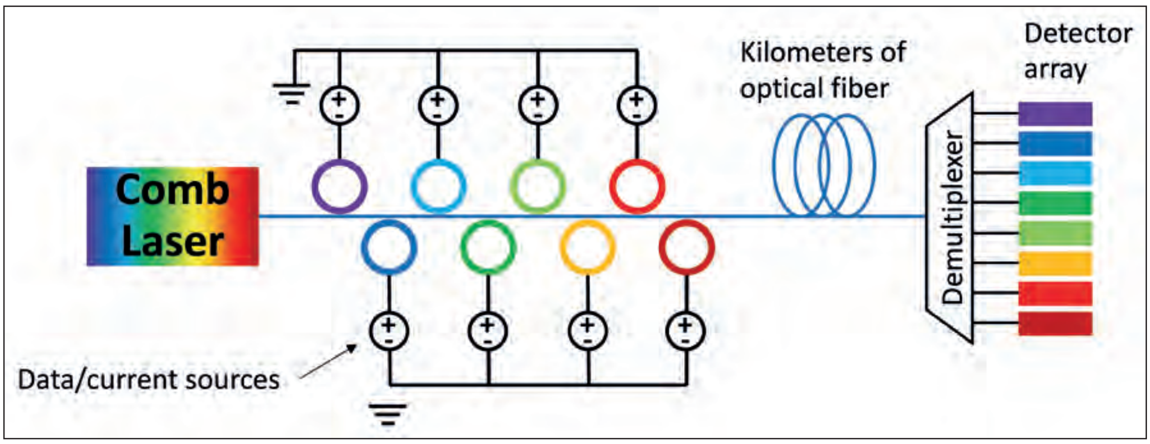


Figure 6. An optical link based on a comb laser. Rather than directly modulating the laser, external modulators are used to encode data on individual comb lines.

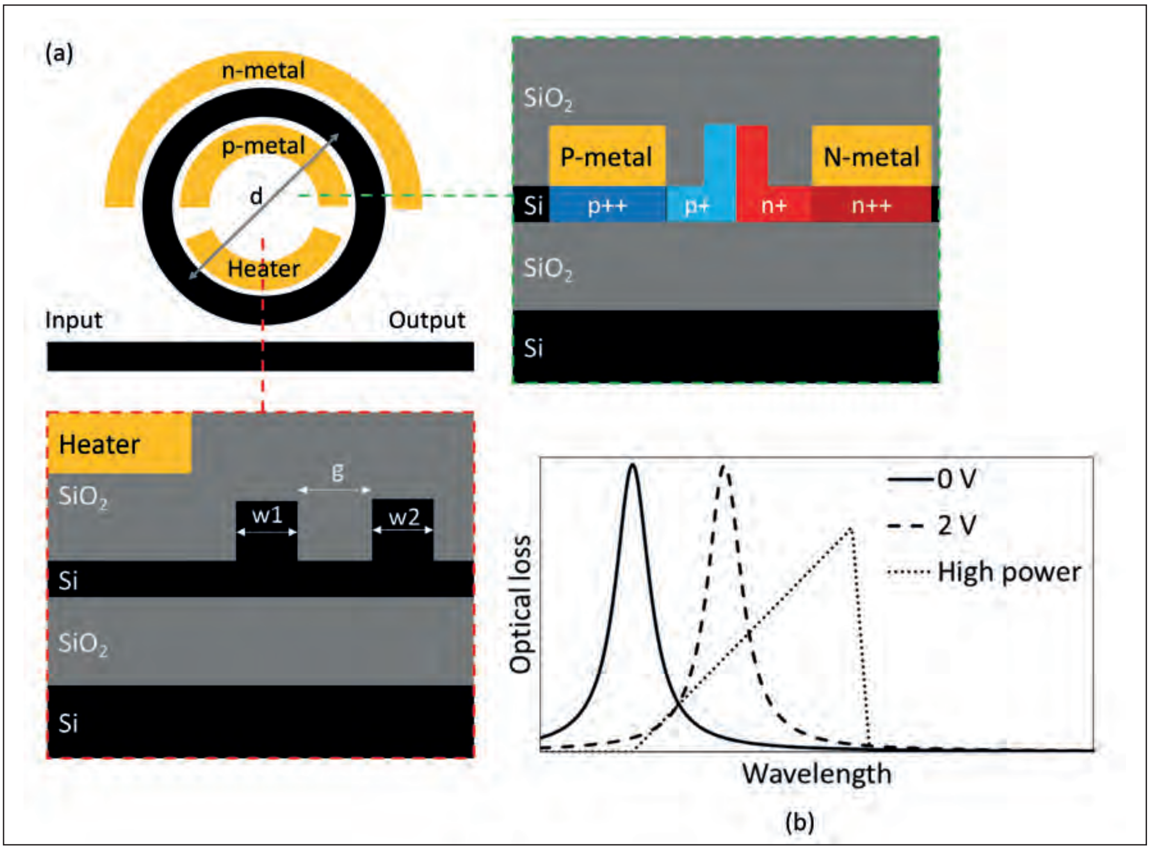


Figure 7. (a) Top-down and cross-sectional diagrams of a micro-ring modulator. (a) The wavelength-dependent loss of a ring modulator has a resonance that can be engineered using parameters *d*, *g*, *w1*, and *w2* in (a). In addition, it can be tuned using a power-hungry heater. Data are encoded by applying a voltage across the *p-n* junction. (b) The shape of the modulator's resonance becomes highly distorted at high optical powers, making pulsed lasers less desirable as a light source.

diameter of the ring, its inner width, and its thickness. One of the constraints of micro-ring modulators is that they impose a limit on optical power. If it is too high, non-linearities degrade the contrast of the resonance, and in turn lower the signal-to-noise ratio of the encoded data (see Figure 7 (b)). Due to this restriction, it is far better to operate comb lasers with a constant optical power. Fortunately, that's a great operating regime for this class of laser, thanks to its gain recovery characteristics.

There will always be a shift in the lasing wavelength of the comb laser, even if the micro-ring is perfect. What's needed is some form of tuning or tracking to maintain a line-up between the ring's resonance wavelengths and the temperature-shifted comb lines. One option is to apply a voltage to the *p-n* junction, but this results in excess optical loss, in the form of free-carrier loss.

The common way to avoid this is to use a resistive heater to locally change the ring's temperature. In turn, this shifts the refractive index of the cavity, and can deliver large changes to the resonance wavelength. However, resistive heaters are wasteful, requiring up to tens of milliwatts to shift the wavelength by just a nanometre. We prefer a more energy-efficient approach, using a capacitor to tune the resonance wavelength. With our design, a layer of semiconductor material is placed on top of the micro-ring, and inserted between is a 20 nm-thick layer of dielectric, such as SiO_2 or Al_2O_3 (see Figure 8). Electrodes are added to the silicon and the semiconductor to form a metal-oxide-semiconductor capacitor. When a voltage is applied to this device, sufficient electrons and holes accumulate at the dielectric interfaces to produce a change in the refractive index of the micro-ring, and its resonance wavelength. As the current flowing through the capacitor is incredibly small – it is only around 100 fA – the resulting tuning is 10^{-9} mW/nm, giving an increase in efficiency of nine orders of magnitude compared with a resistive heater.

To manufacture these comb lasers in high volume, using a high yield, low-cost process, they must be integrated on silicon substrates. Our short-term solution is to take GaAs-based epitaxial wafers, which contain our quantum dot structures, and use a molecular bonding technique to attach them to silicon-on-insulator wafers. We then selectively remove the GaAs substrate to leave a 1-2 μm-thick epitaxial stack on silicon, and process this material in the same way that is used to produce conventional GaAs lasers. However, we have the benefit of using much larger, stronger wafers.

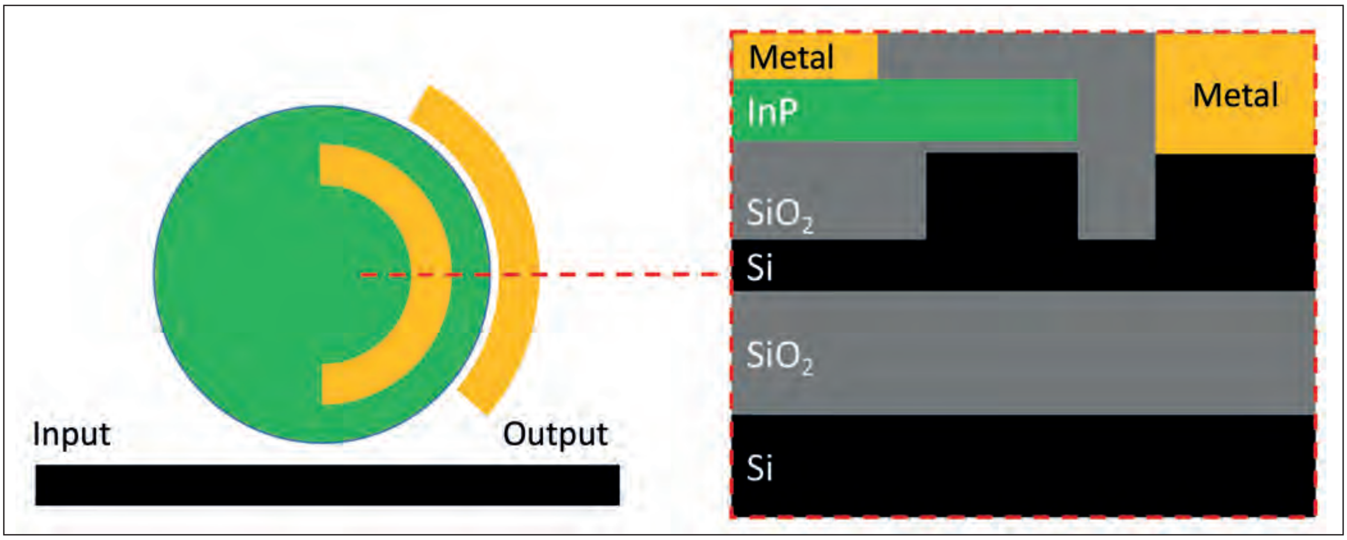
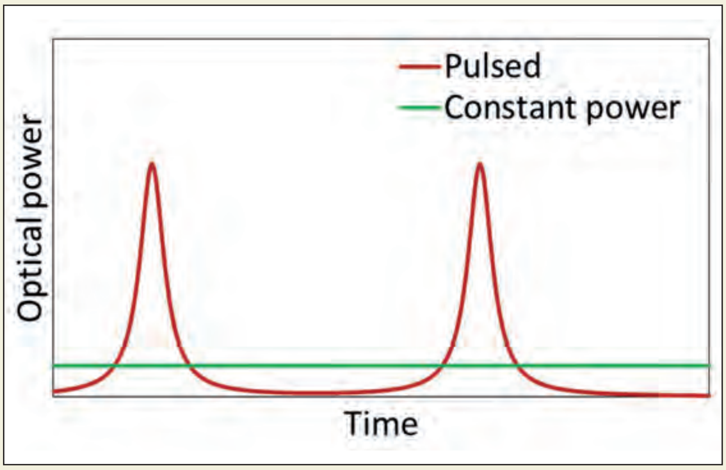


Figure 8. A MOS tuner provides much more efficient resonance tuning than a thermal tuner. When a voltage is applied to the contacts, charges accumulate at the SiO_2 layer, which is between the silicon and the InP. Charge accumulation is sufficient to change the refractive index and thus the resonance wavelength. However, since no current flows through the capacitor, power consumption is negligible.

The problems of pulsed comb lasers

WHEN COMB LASERS produce a pulsed output, or are temporally modelocked, the average optical output power is constant, but the energy of one period is compressed (see figure below). This can cause two problems. One potential issue is that the higher instantaneous power, contained in pulses typically as short as 2 ps, accelerates device failure, such as catastrophic optical mirror damage.

This is particularly problematic in comb lasers, as a failure impacts all channels. The second issue is that the high output power of the peaks impairs the contrast of the resonance, and ultimately reduces the signal-to-noise ratio of the encoded data.



Pulsed lasers are a form of comb laser that emit periodic pulses. The two devices shown here have the same average power, but the pulsed laser has a much higher peak power than the constant-power laser. The presence of pulses can have unwanted consequences such as reduced laser reliability and reduced signal-to-noise ratio of the encoded optical data.

A great strength of this process is that the silicon layer in these lasers provides both a mechanical substrate and an optical waveguide (see Figure 9 (a)). Silicon is ideal for waveguiding – it has a far lower optical loss than those made with GaAs or InP systems, and it allows us to make: high quality laser mirrors; MOS tuners for near zero-power tuning; and vertical grating couplers, which allow rapid, wafer-level device testing. With this approach we have fabricated comb lasers operating up to 100 °C (see Figure 9 (c)), and variants that provide 14 channels for error-free, high-speed modulation (see Figure 9 (d) and (e)).

Longer term, our plan is to produce comb lasers by growing quantum-dot-containing layers directly on silicon. This is far from easy, due to the large lattice mismatch between silicon and GaAs. Left unchecked, this results in a high density of defects that drag down device reliability, and can even kill lasing operation in an instant. Some groups have turned to thick buffer layers to reduce the strain in the quantum dot layers, but this hampers efficient coupling of light from the quantum dot layers to the silicon. Due to this, teams that have made devices that are based on direct growth of quantum dots on silicon have only used silicon as a mechanical carrier.

While comb lasers are very attractive, we are not advocating their use in every optical link. Since all channels in a comb laser are always on, comb lasers are only attractive for dense wavelength division multiplexing links that have a high volume of traffic at all times. Use a comb laser with many channels in a link with little traffic, and lots of power will be wasted by the unused channels, because they cannot be turned off. For links with low and medium levels of traffic, using an array of single-wavelength lasers may offer a more energy efficient solution.

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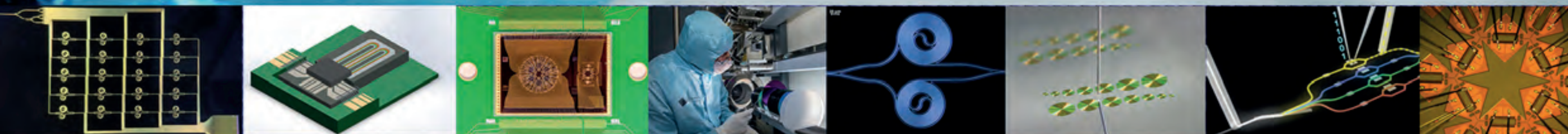

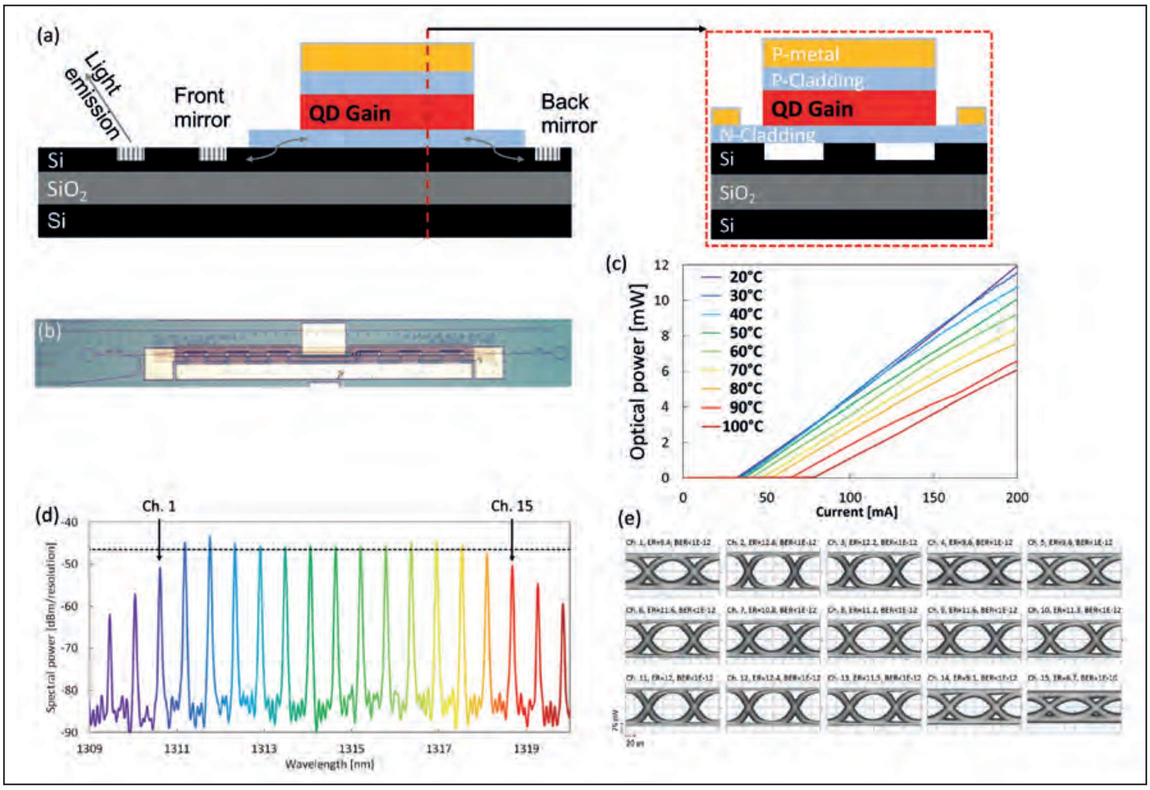

Figure 9. (a, b) Cross-sectional diagrams of a quantum-dot comb laser on a silicon-on-insulator substrate. Thin epitaxial layers between the top silicon and the quantum-dot gain allow efficient transfer of light between them. (b) Top-down photograph of a fabricated comb laser on silicon using wafer bonding. (c) Optical output power as a function of current and temperature showing excellent high-temperature performance. (d) Optical spectrum of a comb laser showing multiple comb lines with a quasi-rectangular shape. 12 comb lines within 3 dB of the peak (dashed line) are observed. (e) Eye-diagrams and bit-error-ratios (using an external modulator) showing error-free performance in 14 of the 15 channels that were measured (the bit error rate is no more than 10^{-12}).

There are two remaining challenges to overcome before comb lasers are ready to light up the next generation of high-performance computers. The first of these is device reliability. Since all channels are created in one laser, when a device fails, it impacts all channels. One way to partly offset this risk is redundancy.

The second challenge is to devise an effective approach to increasing the number of channels. Although the spacing between the channel is inversely proportional to the length of the laser, making a laser longer is not a recipe for success. What happens is that as the channel spacing gets narrower, the individual channel rate has to be reduced to maintain a low cross-talk between the channels. The upshot is that there is no increase in the aggregated bandwidth.

A more promising solution is to increase the width of the optical window for the comb lines. The upper limit for this is determined by the gain bandwidth of the optical amplifier, which is typically 50 nm wide. Through engineering, this has the potential to be increased to more than 100 nm. However, even for 'regular' optical amplifiers with a 50 nm gain bandwidth, the combs that result are typically just 15 nm wide. At present, the reason for this is unclear, but several hypotheses have been suggested.

One possible explanation is spatial hole burning, and another is group velocity dispersion – that there is imperfect mode spacing of a comb, resulting from a wavelength-dependent refractive index. If either of these are the cause, they can be addressed by engineering. Analytical models are being developed to help understand the impact of these phenomena, and experiments are underway to verify the models. When success follows, we shall be a step closer to implementing the efficient, high-speed optical links required to maintain progress in high-performance computing.

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For more information contact:

Jackie Cannon **T:** 01923 690205 **E:** jackie@angelwebinar.co.uk **W:** www.angelwebinar.co.uk
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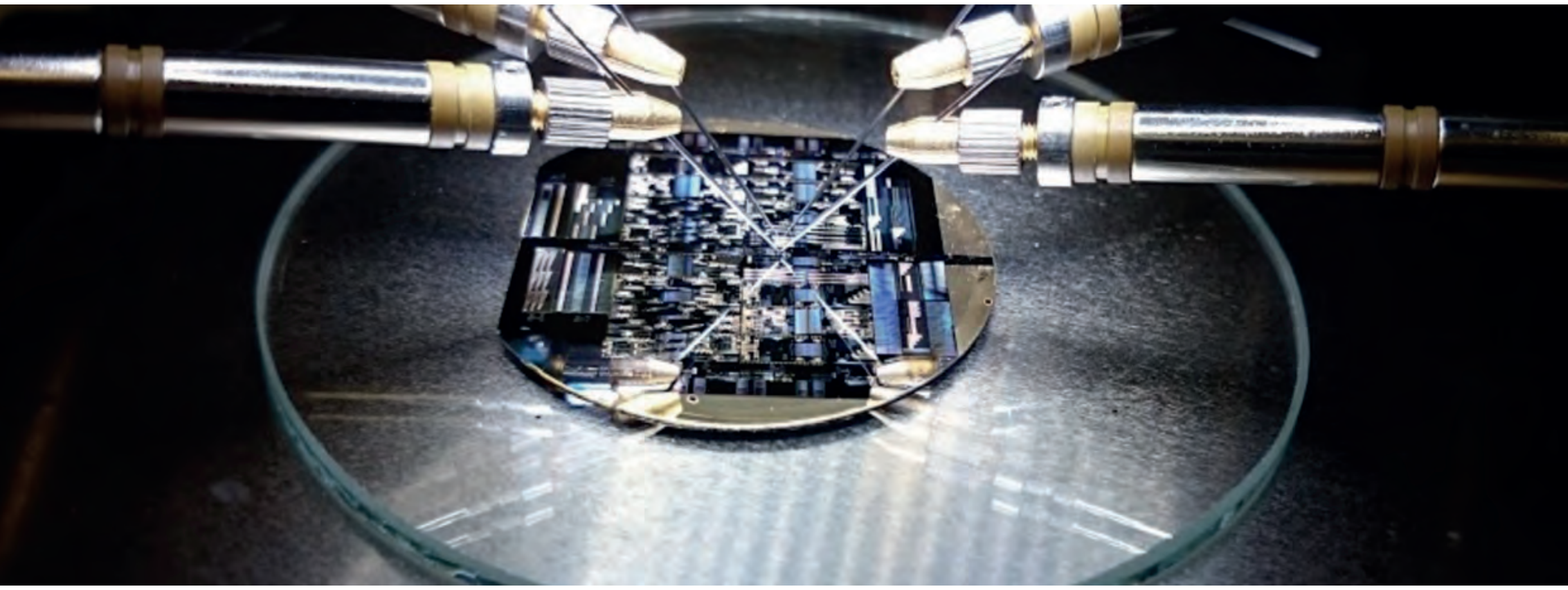


Plug and play characterization

An integrated electrical test platform builds on the advantages of foundry services by offering chip-level test and characterization

BY AXEL SCHOENAU, MORITZ BAIER, FRANCISCO SOARES, GUILLAUME BINET, NORBERT GROTE, JONAS HILT, PETER HELLWIG, RONALD FREUND AND MARTIN SCHELL FROM THE FRAUNHOFER HEINRICH HERTZ INSTITUTE

THERE ARE MANY APPLICATIONS for the InP PIC. It is already deployed in sensing, telecommunication, biophotonics and signal-processing – and it may not be long before it is used in quantum optics, LiDAR and AI. This technology has much appeal in all these applications, due to its low cost and the opportunity to slash the size compared with classical optics.

Manufacturing InP PICs involves several complex, costly processing steps. But this does not have to prohibit researchers at companies and universities from investigating this technology, thanks to the availability of photonic InP foundry services. By sharing wafer space with other customers, fabrication costs for a whole wafer can be distributed between the various parties (see Figure 1). Using a process design kit, each customer can place pre-defined building blocks of active and passive integrated components on the InP wafer according to the foundry's design rules.

Many of these building blocks have to be actively controlled. Current sources are needed to control light sources, such as distributed feedback lasers and distributed Bragg reflector lasers, and also gain sections, thermal optical phase shifters and heaters.

In addition, there is a need for voltage sources, used to control electro-absorption modulators and photodiodes. PICs also feature appropriate metal routing, to facilitate probing and simplify wire bonding to either electronics or an interposer board.

If a customer does not require packaging, bare InP PICs are shipped to the customer in a gel pack (see Figure 1). On arrival, the customer has to undertake experimental verification of the prototype. That's not easy, as it requires measurement equipment with a total price tag of several hundred thousand euros or more, and experience in handling PICs, to prevent them from damage.

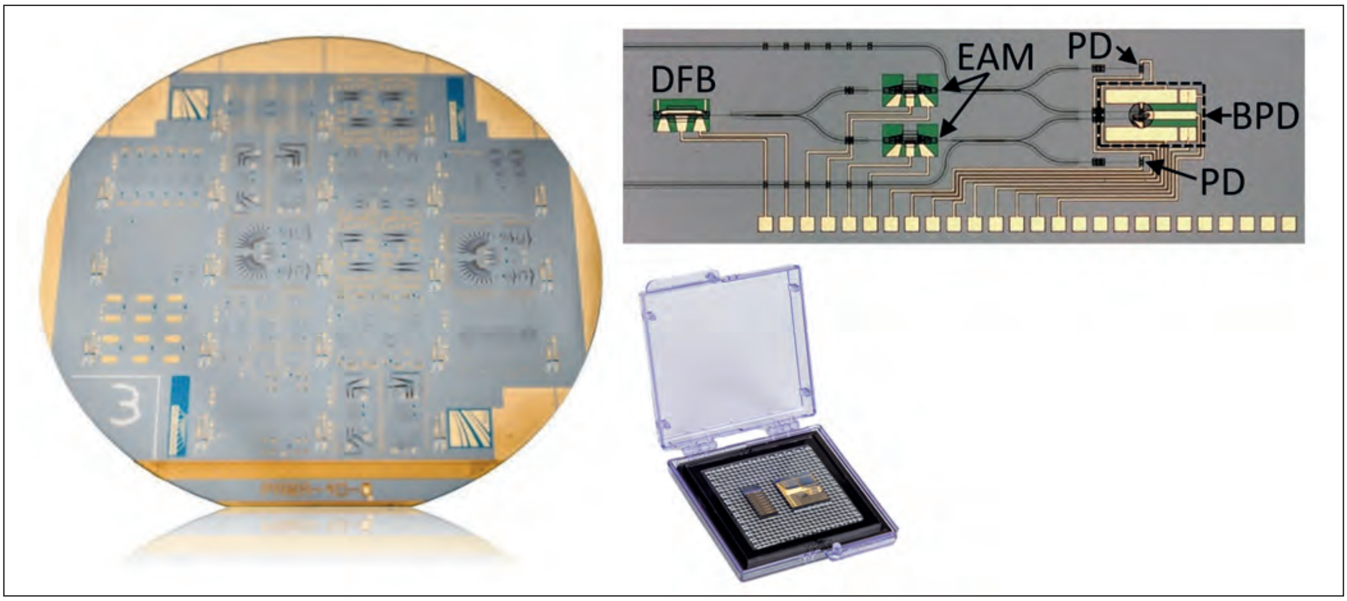


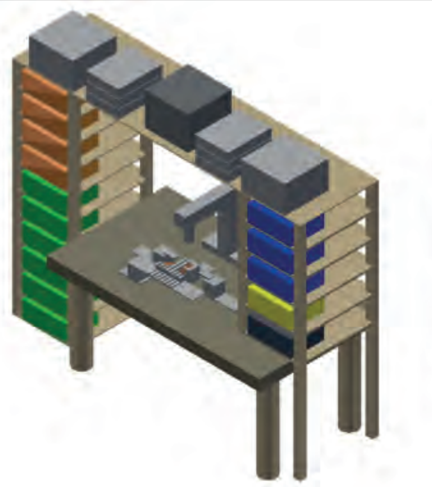
Figure 1. A 3-inch InP based multi-project wafer containing customers' PIC designs and test structures (left). Single PIC with metal routing for on-chip DC characterization of balanced photodiodes (BPDs) (top right). This chip contains distributed feedback lasers (DFBs), electro-absorption modulators (EAMs) and photodiodes (PDs). Bare chips in a gel pack before shipping to the customer (bottom right).

To overcome these daunting obstacles, our team at the Fraunhofer Heinrich Hertz Institute has developed an integrated test platform for generic PICs. Our work builds on the InP PIC foundry services that we offer. Those working in this industry now have the opportunity to access foundry services that are no longer restricted to epiwafer growth and processing, but extend to test and characterization.

Conventional PIC measurements

One of the expenses for engineers carrying out their own PIC testing is the purchase of a temperature-controlled chuck. It is needed to house the PIC and provide mechanical stabilisation, which can be realised with a vacuum. Further expense may be incurred to couple a fibre to the PIC. If that's required, equipment is needed for coarse and fine alignment. A translation stage for each fibre ensures coarse alignment to the waveguides or on-chip spot size converters, while fine alignment can be realised with piezo motors with sub-micron step sizes. An example of a PIC measurement set-up is illustrated in Figure 2.

A popular choice for the input light source for the PIC is an external cavity laser. It provides well controlled wavelengths and powers. Experimental set-ups also tend to include optical switches, used to direct out-coupled light to detection and analysis instruments, such as optical spectrum analysers and photodetectors. As testing may also involve electrical biasing and sweeps, there is the need for current and voltage sources, in combination with corresponding meters. To apply these currents and voltages to PIC building blocks, researchers often use probe needles (see Figure 3).



Mechanical	Optical	Electrical DC	Electrical RF
Stepper motors	Fibres	TEC	RF probes
Piezo motors	ECL	DC probes	
Motor controller	Polarimeter	I-sources	AWG
Manual stages	Polarization controller	I-meters	PRBS
Microscope		V-sources	RTO
Vacuum pump	Switch	V-meters	...
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Figure 2. Schematic of a conventional PIC measurement set-up (left). Listed mechanical, optical and electrical systems (right).

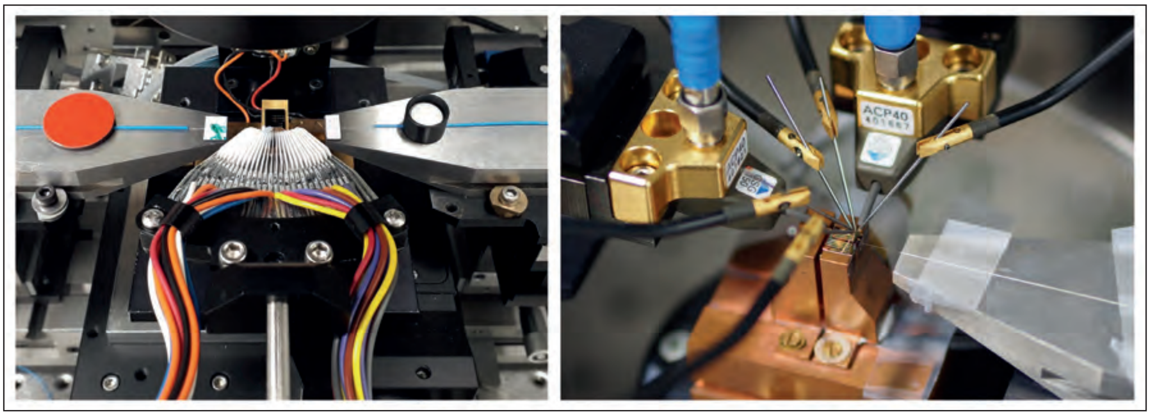

Figure 3. Electrical probing of a PIC with a 26 needle DC multiprobe (left), RF probes and single needles contacting a PIC (right, image courtesy of Weiming Yao, Department of Electrical Engineering, Photonic Integration, TU Eindhoven).

Measurements of data transmission require additional equipment, such as arbitrary waveform generators, pseudo-random bit stream sources and real-time oscilloscopes. If high-frequency measurements are to be made, RF-probes have to be placed on the PIC besides biasing needles. That's tricky, requiring many probes to be positioned on a chip that is smaller than a finger nail.

Simplifying evaluation

Given all these challenges associated with evaluating a PIC, affordable plug-and-play characterization is highly desirable. We are giving this to our customers with our new PIC evaluation set-up, which we have named PIConnect. By featuring integrated laser drivers and general purpose current and voltage sources, it enables parallel operation of PIC building blocks. Researchers investing in a PIConnect receive a mainboard, which contains all sources plus a plugged-in micro-controller board, as well as a PIC Board on a cooling stack to assemble the PIC (see Figure 4).

The mainboard contains eight current sources, eight voltage sources, four laser drivers, and one temperature controller that supports a 10 kΩ thermistor temperature sensor. The temperature controller drives currents up to ±1.5 A.

Each of the current sources provides an output current of up to 200 mA at up to 5 V. Voltage monitoring is integrated. For the voltage sources, the output can be adjusted between -10 ... +10 V. The current, which has integrated monitoring, cannot exceed 20 mA. Laser drivers can deliver currents up to 200 mA at a maximum voltage of 3 V. For this first-generation product, all measurements are made with 12-bit resolution.

To evaluate the PIC, it has to be mounted on the PIC Board and bonded to equally spaced pads. Connecting the PIC Board to the mainboard is done by a flexible flat cable containing 50 wires. The PIC Board is positioned on a cooling stack with a 20 mm by 20 mm Peltier element that enables precise temperature controlling through a 10 kΩ thermistor. Within this set up, the Peltier element is directly connected to the thermo-electric controller on the mainboard (see Table 1 for details of the hardware specifications).

To access the information generated by PIConnect, it is connected to a PC via Ethernet using a web interface. A Python-based graphical interface enables the setting of constant currents and voltages, and

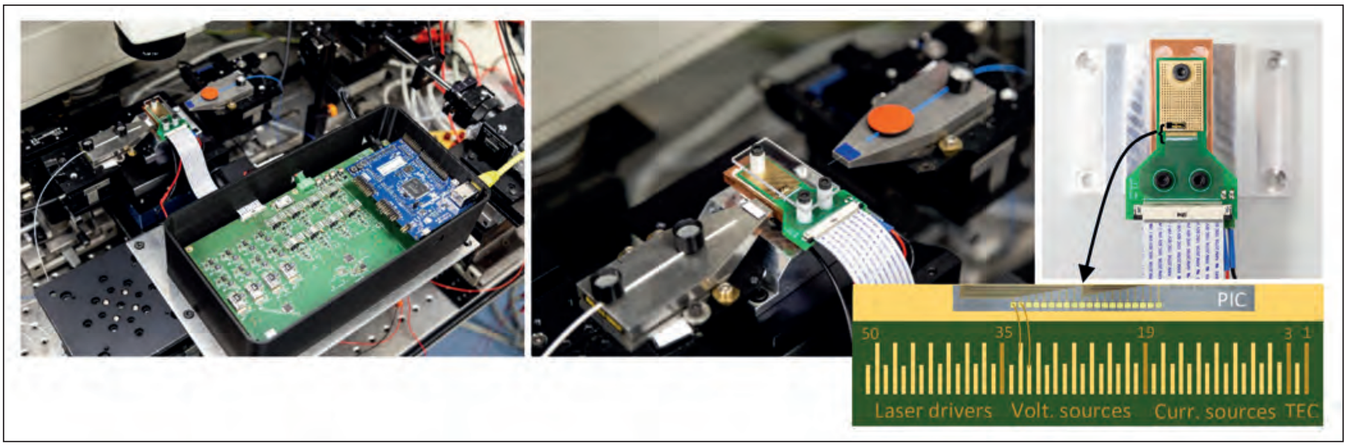

Figure 4. PIConnect comprised of mainboard (that has 8 current sources, 8 voltage sources, 4 laser drivers (Thorlabs MLD203P1) and one temperature controller (Thorlabs MTD415T)) with a microcontroller board (SAME70 XPLAINED) and PIC Board integrated in an existing measurement set-up (left). Photograph of the PIC assembled on the PIC Board with a Peltier element and mechanical mounting plate (centre). Fibre coupling is undertaken using tapered fibres and piezo actuators. Glued and wire-bonded PIC on a PIC Board (top right) and pinout of the PIC Board bond pads (bottom right; shows only exemplary wire bonding). The pitch between two adjacent pads is 200 μm.

Controller/Sources	Amount	Pin	Specs	Resolution	Monitoring
TEC controller	1	1-2	10 kΩ thermistor, ±1.5 A	0.7 mA	
Current source	8	3-18	Max. 200 mA @ max. 5 V	50 µA, 1.2 mV	Voltage
Voltage source	8	19-34	-10…+10 V @ max. ±20 mA	5 mV, 10 µA	Current
Laser driver	4	35-50	Max. 200 mA @ max. 3 V	50 µA, 0.7 mV	

Table 1. Components of the mainboard with specifications and pinout.

applying sweeps within defined ranges (see Figure 5). We recommend using predefined Python written functions when embedding PIConnect into an existing measurement set-up. Adopting Python's Application Programmable Interfaces equips the user with complete control of automated measurements in the kilohertz-regime – the only limit is the web interface speed.

Demonstrating capability

To demonstrate the capability of our PIConnect, PIC Board and mainboard are introduced to our existing PIC measurement set-up, which is shown in Figure 4. We use a polarimeter PIC as our showcase device under test. This chip has a Mach-Zehnder based structure, which uniquely maps measured photocurrents to the corresponding input polarization of the light. The polarimeter PIC works for wavelengths across the entire C-band and beyond, but here it is demonstrated at just 1530 nm. We presented the details of this PIC at OFC 2019.

During this test we launched 595 distinct polarizations across the Poincaré sphere into the polarimeter. The polarization states of the light are recorded using blue circles (see Figure 7). For this measurement, five integrated photodetectors are biased at -2 V, and at each polarization the photocurrents are recorded by PIConnect.

This test platform produces a mean mapping accuracy of around 1.8°. This low value highlights the competitive performance of PIConnect. We will offer PIConnect as an additional service to our customers. We know that they will welcome its introduction, as it is more than ten times more cost effective than the laboratory equipment normally used for PIC characterization, such as the combination of multiple dual-channel source meters, a Peltier controller and probing mechanics.

Note that it is possible to use two or more mainboards in parallel. This offers a straightforward approach to scaling the number of laser drivers, and current and voltage sources. To adopt this approach, the PIC Board must be re-designed so that it can connect several flat cables.

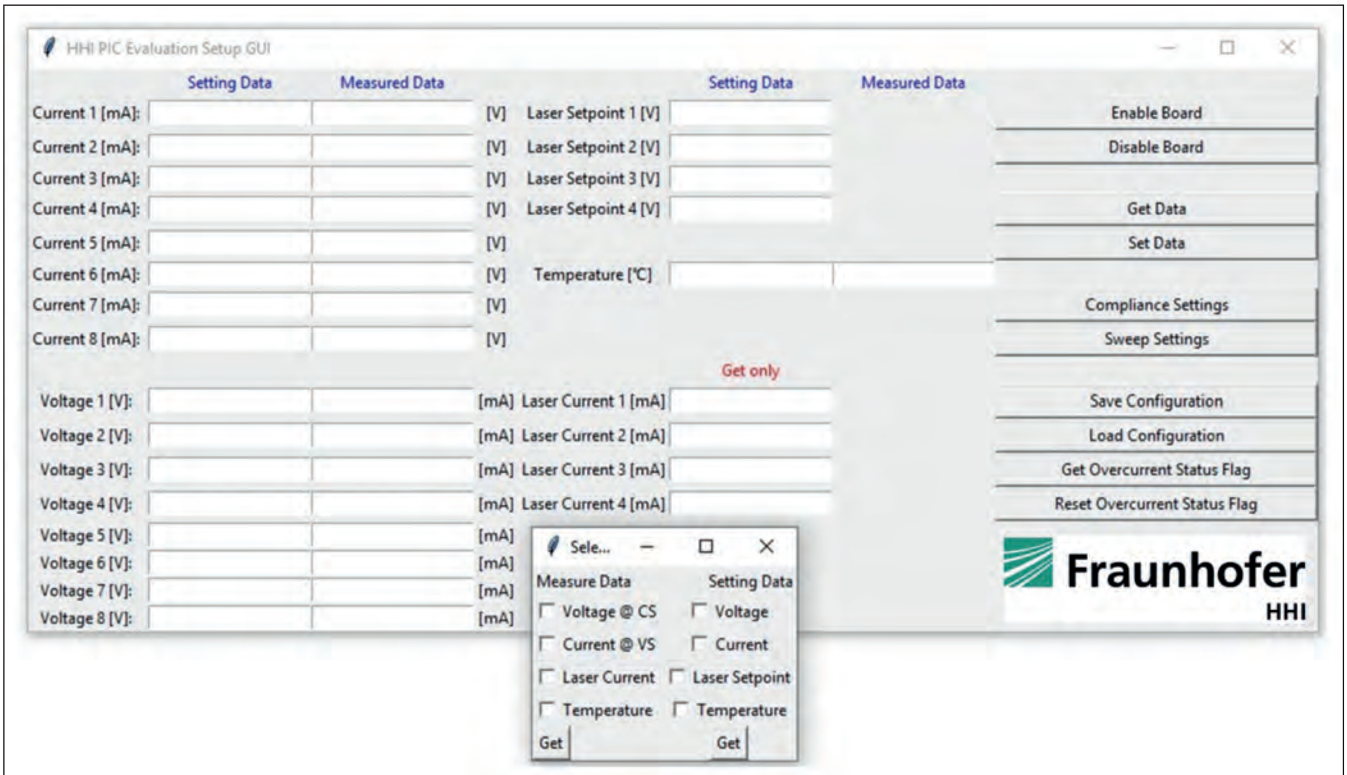

Figure 5. Python-based graphical user interface for setting and getting measurement parameters. Single sweeps, saving and loading are also possible.

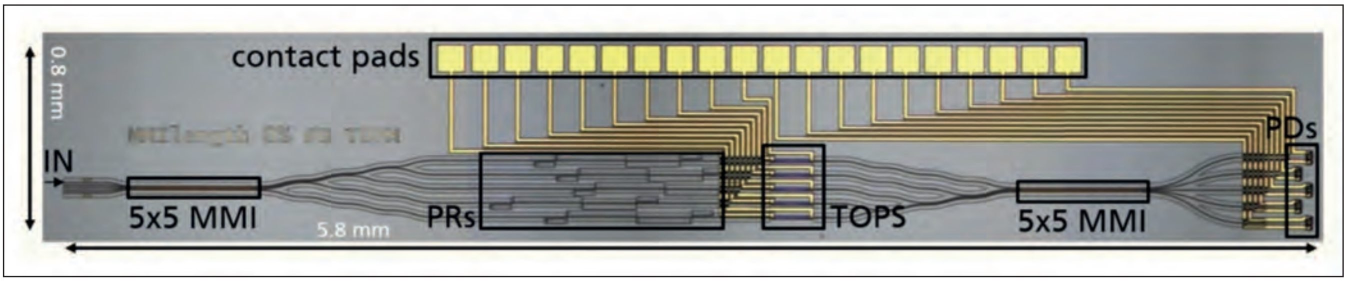

Figure 6. Integrated polarimeter PIC. Light is coupled from a fibre into one of the input ports on the left side. Five on-chip photodetectors (PDs) measure the photocurrents, and five thermal-optic phase shifters (TOPS) tune the configuration. The PIC further consists of polarization rotators (PR) and multimode interferometers (MMI).

We are continuing to work on simplifying PIC characterization. Through our involvement in the EU Horizon 2020 project InPulse – short for Indium-Phosphide Pilot Line for up-scaled, low-barrier, self-sustained, PIC ecosystem – we are working on automated, standardised routines to characterise PICs. The test platform will be exploited to offer a rigid, predictable and reproducible verification mechanism for process design kit contents and customer designs.

Together with the joint European platform for photonic integrated components and circuits (JePPIX), we will be offering PIConnect as an additional option to the customers of multi-project wafer runs. Our next step, enabled by general PIC design rules, is to make PIConnect available to customers using other foundries. A longer term goal is to integrate optical coupling and RF feeds, to improve the functionality of PIConnect. Through our efforts, lower-cost, simpler options for testing InP PICs are going to be available to more players within this industry – and that will help to grow the market for this technology.

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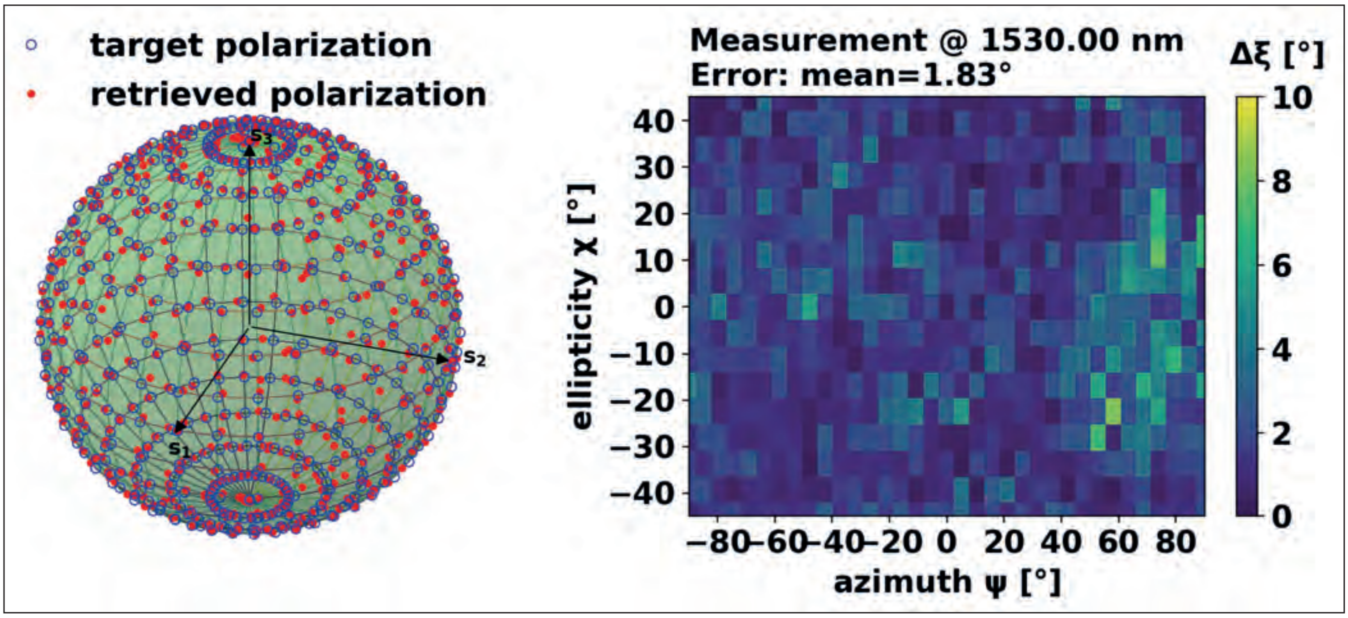

Figure 7. Experimental results at a wavelength of 1530 nm using PIConnect. On the left is a Poincaré sphere, 595 target (blue circles) and retrieved (red dots) polarizations are visualised. The corresponding heatmap on the right shows the measurement accuracy Δξ of the PIC. Δξ gives the angular measurement error on the Poincaré sphere. For this measurement the average is 1.83°.

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